Dear Editor,

Thank you for inviting us to submit a revised manuscript. Below we have summarized the important changes made to the manuscript in response to the reviewer and editor comments:

1. We have rewritten portions of the manuscript to clarify the purpose of our paper and better articulate the potential impact of our work.
2. We removed references to unit testing throughout the text and in the title to eliminate confusion. We replaced the phrase with "impulse response tests," which is more descriptive and used elsewhere in the literature.
3. We revised the methodology section to include a clearer description of the fundamental impulse tests conducted in our study and the parameters used in the SCMs.
4. We included the input parameter files with the supplementary data files, which are now available on Github.
5. We made an error when applying the 4xCO_2 concentration step in the AR5-IR model and, thus, updated Figure 4 in the manuscript and any numerical references to those results in both the main paper and supplement. This change did not impact the overall conclusions of our paper.
6. We revised Table 1 in the manuscript to report the integrated temperature responses of the SCMs to the different perturbations, rather than a scale of performance. We believe this change addresses reviewer concerns about the concluding section.
7. We added large portions of text to the concluding section of the revised manuscript to describe the results reported in the revised Table 1.
8. Several minor text changes were made to improve readability and understanding.
9. We added and updated several citations to both the manuscript and supplement.
10. We added several sections to the supplement based on the reviewer comments and our responses including: S2.4, which explores the differences between AR5-IR and FAIR; S3.1, which explores the CMIP5 data used in the manuscript in greater detail; and S11.2, which explores additional sensitivity experiments in the SCMs using MAGICC6.0-derived parameters.

Response to Reviewer #1

Comment: This manuscript presents the responses of a set of climate variables in five different simple climate models (SCMs) to a selected set of impulses. The results of the global temperature response to one of these impulses (a step quadrupling of atmospheric CO2-concentration) is compared to the corresponding responses in an ensemble of CMIP5 Earth System Models (ESMs). The simple models belong to two categories: the idealized SCMs (AR5-IR and FAIR), and the comprehensive SCMs (Hector v2.0, MAGICC 5.3, and MAGICC 6.0).

Response: We appreciate that you took the time to provide an accurate summary of our work.

Changes in Manuscript: None.

Comment: Testing of simple models against more complex ones is interesting and relevant to ESD, but the interpretation of results are difficult, since it is not obvious that a complex model represents specific aspects of reality more correctly than a simple model.

Response: We appreciate that you agree this work is interesting and relevant to ESD. Comparing simplified models to more complex models is a technique often utilized in the literature (e.g., Joos et al., 2013) and we also employ this technique. We compare the responses of idealized SCMs to comprehensive SCMs and comprehensive SCMs to CMIP5-class models. In our paper, we do not necessarily expect individual models to represent reality, but instead rely on the multi-model mean to ground our comparisons. It is well established that the multi-model mean behavior of the complex models replicates a broad suite of observations better than any individual model (e.g., Figure 9.7, Flato et al. 2013). Our subsequent responses will also address this comment.

Changes in Manuscript: We added text to clarify our comparison of the individual models to the multi-model mean.

Comment: The paper does not seem to present novel concepts, ideas, tools or data. The concept of "unit testing" seems to be a misnomer here, as pointed out in the comment by dr. Nicholls.

Response: We strongly believe this paper does present a specific application of concepts that are new to the literature. Though fundamental impulse tests have been used in the literature, our manuscript employs these existing techniques in a novel way. This is the first study in the literature to rigorously evaluate SCMs using impulse-response tests. SCMs are widely used in the literature and in decision-making context, e.g., within Intergovernmental Panel on Climate Change (IPCC) Reports, coupled with Integrated Assessment Models. In fact, a paper describing a commonly used SCM, MAGICC 6.0, has been cited 371 times in the literature. Another model, the impulse response model used in the IPCC Fifth Assessment Report (AR5-IR), is heavily used by the scientific community to support decision making. Despite their importance, the fundamental responses of SCMs are not fully characterized and we provide a set of tests that we recommend as a standard evaluation suite for any SCM. Further, the U.S. National Academies of Science (2016) specifically suggested that SCMs be, "assessed on the basis of [the] response to a pulse of emissions," which we do here.

We have added portions of the text above to the revised manuscript introduction to make a more compelling case for our work.

We address the comment about the phrase "unit testing" below.

Changes in Manuscript: We added language to the manuscript that better articulates the potential impact of our work. Some of this language is derived from this response

Comment: The conclusions are not very clear, and the concluding section is very short.

Response: We will expand the conclusion in the revised manuscript to include a discussion of Table 1, and we copied the revised text into this response below.

Changes in Manuscript: We amended Table 1 in the conclusion section and elaborated on our findings more thoroughly in the revised manuscript.

Comment: The authors do not present reflections around the assumptions underlying the conclusions.

Response: We remind the reviewer that we are evaluating the behavior of models and their responses to fundamental impulse-response tests and are not providing information on the underlying mechanisms of the models. The underlying mechanisms are explored by the individual modelling groups in their publications, which we have cited in our manuscript.

Changes in Manuscript: We added text to the revised manuscript clarifying that the purpose of our paper to employ impulse response tests to evaluate the behavior of the SCMs.

Comment: Model parameters are not given and discussed (not even in the supplement), which has been a source of frustration and confusion for this referee.

Response: We apologize for any confusion in our omission of model parameters. We agree that model parameters are very important for understanding how these models differ. We will add the model parameter files to the supplemental materials so that readers can more easily replicate our results.

Changes in Manuscript: We have added the parameter input files for each SCM to the supplementary data.

Comment: Reasonable credit is given to related work.

Response: Thank you for the positive comment.

Changes in Manuscript: None.

Comment: The title should find another term than "unit testing".

Response: We use the phrase "unit testing" with the understanding that this phrase is commonly used in software as we mentioned in the Supplement. Similar to meaning of "unit testing" in software, we are testing the SCM in the simplest way possible, by determining the impulse response of specific model sub-systems such as CO_2 and CH_4 gas cycles, and the forcing to temperature response of each model. Though we believe our use of the phrase is consistent with its use in software, as we replied to the Short Comment, we will update the language in the manuscript and title to "fundamental impulse tests" to avoid confusion.

Changes in Manuscript: Throughout the revised manuscript, including in the title, we now refer to our tests as "fundamental impulse tests."

Comment: The abstract reflects the content of the paper, apart from the term "unit testing".

Response: Thank you for the comment. We addressed the use of the term “unit testing” in the response above and will instead use the phrase “fundamental impulse tests”.

Changes in Manuscript: None that were not already adopted.

Comment: The presentation and language is adequate.

Response: Thank you for providing comments on the structure of the paper.

Changes in Manuscript: None.

Comment: FAIR is a generalization of AR5-IR to include state dependence of the carbon cycle (Millar et al., 2017). For the experiments shown in Figures 1 and 4 (temperature responses to CO2-forcing), the carbon-cycle module is not active, and from my understanding of the description of FAIR in Millar et al., 2015, the two models should be identical when temperature response to CO2 concentration is simulated. However, in both figures the responses of the two models are very different.

Response: We do expect slight differences in the response of FAIR and AR5-IR to a unit forcing. According to Equation 8 in Millar et al., 2017, FAIR will have a differential response to change background CO_2 concentrations. By contrast, AR5-IR parameterizes the climate response to a unit forcing, R_T, using a sum of exponentials as given by Equation 8.SM.13 in Myhre et al., 2013:

$$R_T(t) = \sum_j \frac{q_j}{d_j} e^{\frac{-t}{d_j}}$$

Values of the R_T input parameters, q_j and d_j, are available in Table R1 of this response, where j=1,2 represent the timescales of the fast and slow ocean response. We note all parameters are independent of background concentration in AR5.

Changes in Manuscript: We added specific references to the differences between FAIR and AR5-IR to the manuscript and included the language from our response above in the supplement (see S2.4).

Comment: If the models are identical in this mode this can only arise from different choices of the time-constant parameters in the simulations of AR5-IR and FAIR. From the figures it looks like the time constants for temperature response in AR5-IR are those used originally by Myhre et al., 2015 (Table 8.SM.11, d1 = 8.5 yr and d2 = 409.5 yr), while in FAIR they look more like the choice of Millar et al. 2017 (d1 = 4.1 yr and d2 = 239.0 yr).

Response: As we mentioned above, the FAIR and AR5-IR responses will differ. And we did use the time constant parameters representing the thermal equilibrium of the deep ocean (d2) and the thermal adjustment of the upper ocean (d1) from Myhre et al., 2013 rather than from Millar et al., 2017. We are testing the model responses as they would be ‘out of the box’ and only make modifications if required for the models to run, as was the case for Hector v1.1 to handle a $4xCO_2$ concentration step.

However, to address your comment we have included below additional model responses from the AR5-IR model using parameters from Millar et al., 2017. The parameter choices are available below in Table R1. We will add this information to the Supplement.

Table R1 Parameter values for the simple impulse-response model, AR5-IR

Parameter (Units)	Value – AR5-IR (from Myhre et al., 2013)	Value – AR5-IR-var (from Millar et al., 2017)	Guiding analogues
α (Wm^{-2})	5.35	5.395 (α = F2x/ln(2); F2x=3.74)	CO_2 RF scaling parameter
q_1 ($KW^{-1}m^2$)	0.631	0.41	Thermal adjustment of the upper ocean
q_2 ($KW^{-1}m^2$)	0.429	0.33	Thermal equilibrium of the deep ocean
d_1 (year)	8.4	4.1	Thermal adjustment timescale of the upper ocean
d_2 (year)	409.5	239.0	Thermal equilibrium timescale of the deep ocean

Figure R1 shows the temperature response from a CO_2 concentration impulse in several SCMs, including the AR5-IR response found using the Millar et al., 2017 time constants, which we refer to as "AR5-IR-Millar-parameters" in this figure. We note that the AR5-IR-parameters response is still not identical to FAIR because FAIR has a differential response to change background CO_2 concentrations.

We note that, while the Millar et al., 2017 parameters in table R1 may provide a better short-term fit, they underestimate the long-term response of the ocean. The long-term ocean thermal time scale, which can only be estimated using multi-century model runs, is known to be longer than 200 years from basic physical principles (as seen in the original literature cited by the AR5 model, which used longer model runs to inform those parameters). While this may be an acceptable tradeoff if this model is only going to be used over a 100-year timescale, this will inevitably lead to bias on longer and longer time-scales. The simple climate models tested in this study are used for a variety of purposes and over a range of time-scales. This illustrates why we use the original parameters of the models as set by their designers.

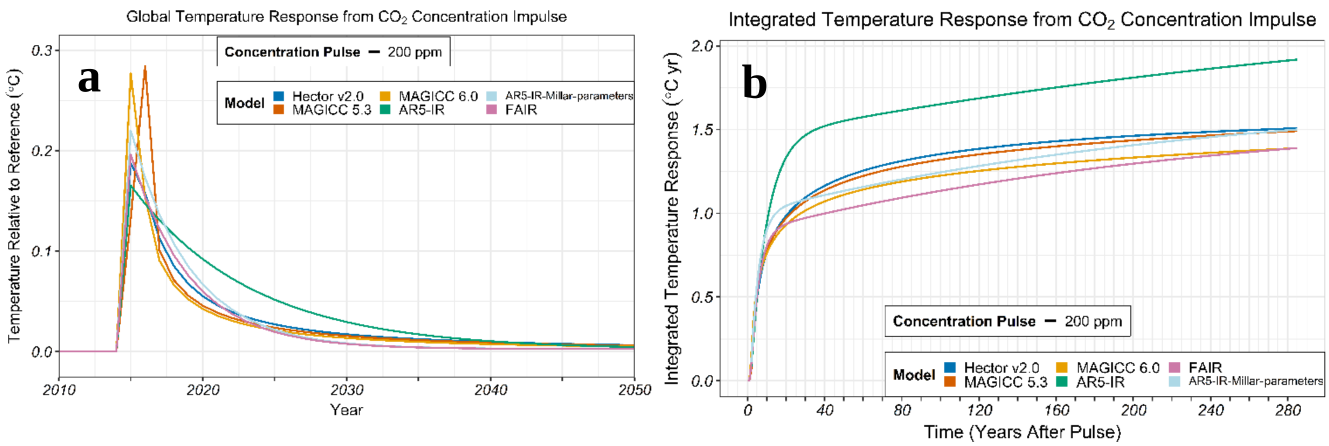

Figure R1 Global mean temperature response (a) and integrated global mean temperature response (b) from a CO_2 concentration perturbation in SCMs (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, AR5-IR – green, FAIR – pink, AR5-IR-Millar-parameters –light blue). The time-integrated response, analogous to the Absolute Global Temperature Potential, is reported as 0-285 years after the perturbation.

Changes in Manuscript: This response was added in its entirety to the revised supplement (see S2.4) to make the differences between AR5-IR and FAIR easier for readers to identify and understand.

Comment: Moreover, if I have got this right, then AR5-IR and FAIR are not only identical models in the simulations shown in Figures 1 and 4, they are also both linear (the nonlinearity in FAIR is in the carbon-cycle module).

Response: A nonlinearity is also present in FAIR based on Millar et al., 2017 Equation 8 as noted above.

Changes in Manuscript: None that were not already adopted.

Comment: For a linear response, the time-integrated temperature response shown in Figure 1b and the response to a step forcing shown in Figure 4 are identical, apart from a multiplicative constant depending on the relative strength of the forcings used in Figure 1 and 4. However, in Figure 1b the FAIR response curve is well below the AR5-curve, while in Figure 4 it is well above. For linear, identical models this is possible only if ratio between the climate sensitivities (ECS) of AR5-IR and FAIR is chosen larger in the simulations for Figure 1 than for Figure 4.

Response: We used consistent ECS values throughout our experiments, unless otherwise noted, and we do want to thank you for your careful comments. We made an error in applying the $4xCO_2$ concentration step in the AR5-IR model, which resulted in the response being significantly lower than it should have been. Figure R2 in our response provides the updated results and is consistent with Figure 1b. We have updated the manuscript and supplement to reflect the amended figure, and we note that this change does not impact our overall conclusions that, "Fundamental forcing tests, such as a $4xCO_2$ concentration step, show that the SCMs used here have a faster warming rate in this strong forcing regime compared to more complex models. However, comprehensive SCM responses are similar to more complex models under smaller, more realistic perturbations (Joos et al., 2013)."

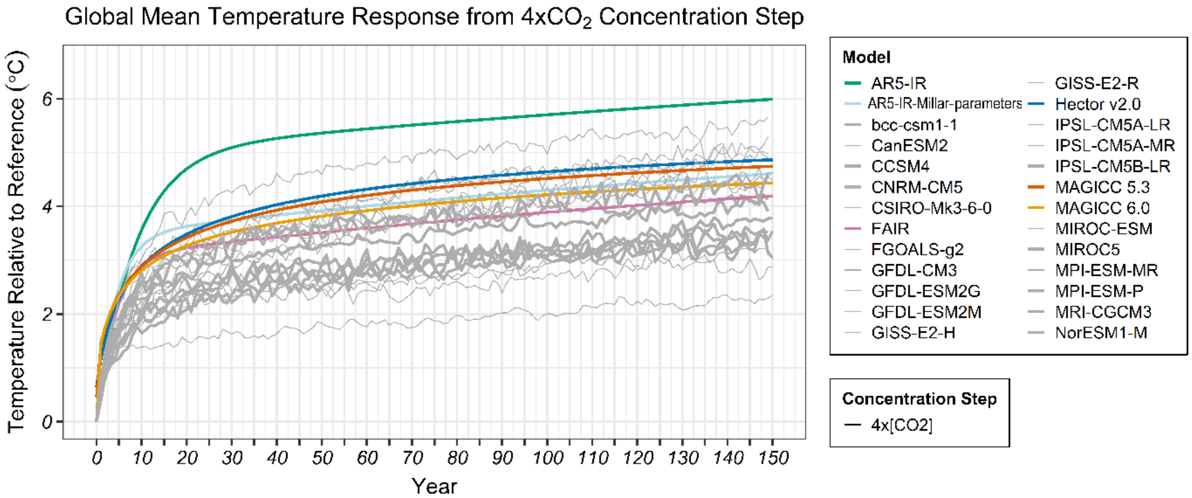

Figure R2 Global mean temperature response from 4xCO_2 concentration step in CMIP5 models (grey) and SCMs (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, FAIR – pink, AR5-IR – green, AR5-IR-Millar-parameters – light blue). A climate sensitivity value of 3°C was used in the SCMs and the thick lines represent CMIP5 models with an ECS between 2.5 - 3.5 °C.

Changes in Manuscript: Based on this comment, in the revised manuscript we updated Figure 4 after mistakenly applying the 4xCO_2 concentration step in AR5-IR, which did not impact our over conclusions. We updated figures and numerical results in the main paper and supplement to reflect this update to Figure 4 and added the language mentioned in the response above.

Comment: In section 3.3 (line 209) the authors write: "Differences between the model responses to a finite pulse (Fig. 1) and a large concentration step (Fig. 4) demonstrates the expected bias in AR5-IR under larger perturbations." This sentence shows that the authors attribute the different relative response between the two models in Figure 1 and 4 to nonlinear effects in FAIR. While FAIR has a weaker response on decadal time scales than AR5-IR under the the small temperature perturbations in Figure 1, the response is stronger than AR5-IR under the stronger forcing in Figure 4, i.e., if model parameters are unchanged, this amplification must be due to a strong nonlinear feedback. The authors need to clarify the source of this nonlinearity in FAIR.

Response: We apologize for the confusion, which we believe it is resolved by updating Figure 4 in the manuscript with Figure R2 in this response. The source of the nonlinearity in FAIR is in the forcing component.

Changes in Manuscript: None that were not already adopted.

Comment: The total forcing response to CO2 and CH4 emission impulses shown i Figure 2 show quite small spread over the SCMs. Unfortunately the FAIR response is not plotted in that figure, but the AR5- response does not differ drastically from the comprehensive SCMs. This indicates that the carbon-cycle module of the idealized and comprehensive models behave rather similarly. The substantial difference between AR5-IR and the rest appears when the resulting temperature response is displayed in Figure 3a, and also in the temperature response to BC emission in Figure 3b. This is all consistent with Figure 1; the time constant d1 for the temperature response in AR5-IR is too high. Fitting a two-box model to the multimodel mean in the 16 member ESM-ensemble considered by Geoffroy et al., 2013 yields d1 = 4.1 yr, which is about half the e-folding time observed for AR5-IR in Figure 1a and 3b. This supports the assertion that the mismatch between AR5-IR and the other SCMs is just a question of a bad choice of model parameters.

Response: As we mentioned above, we tested these models using their default parameter values unless a change was required for the model to successfully complete an experiment. Though we take the reviewer's point about the importance of parameter choice, we note that the definitions and meanings of each parameter are not consistent across the SCMs used in this manuscript. For example, using the ocean component as an example we find that the vertical diffusivity parameter is not defined in the same way across the comprehensive SCMs, and is completely absent from the idealized SCMs where it is implicitly represented by the parametrized ocean timescale values. This is why we use the models as parameterized "out of the box" in the same manner that users of these models do.

Changes in Manuscript: In the methodology section of the revised manuscript, we added a paragraph specifically discussing the parameter choices, and added additional explanation in the revised supplement (see S2).

Comment: Since no use of observation data is made in this paper, the benchmark to assess the performance of the SCMs are the complex ESMs. The temperature response to a step in BC emission is claimed (in S12) to level off much more slowly in SCMs than in the NorESM model, suggesting that the SCMs do not capture aerosol dynamics correctly, but otherwise the comparison with ESM responses is limited to the ensemble of 4 × CO2 step forcing simulations. Unfortunately, the spread over the ensemble of ESM responses in Figure 4 is so large that it cannot be used to validate the SCMs.

Response: We first point out that our primary purpose in this paper is to evaluate the fundamental behavior of the simple climate models. We do this by both comparing them to each other, and also, in the limited cases where this is possible, to more complex models (Joos et al., 2013). We compare against the suite of complex model results because it has been shown that the multi-model mean behavior of the complex models replicates a broad suite of observations better than any individual model (e.g., Figure 9.7, Flato et al. 2013). Also see the next response, below.

Changes in Manuscript: We added some of this response language to the revised manuscript conclusion section.

Comment: In Figure S22, responses for the three comprehensive ESMs are plotted for two other ECS values, 2.1 and 4.7 degrees. For ECS=2.1, the results are in the mid-range of the ESM-ensemble, while for ECS=4.7 the responses are outside (above) this range.

Response: We changed the ECS values in the SCMs to illustrate the effects of parameter selection on the model responses. We found that spanning the range of complex model ECS values still resulted in stronger SCM responses, which supports the conclusion in our main paper that the SCMs have a faster warming rate under strong forcing regimes compared to more complex models. We revised the supplemental text around Figure S22 to state this as well.

In response to Reviewer #2, we have also expanded the revised supplement to include the effects of climate sensitivity and ocean diffusivity parameter selection on the SCM responses.

Changes in Manuscript: We amended the text around the figures to note that the SCMs have a faster warming rate under strong forcing regimes compared to more complex models. We also added the discussion from Reviewer #2 to the supplement (see S11.2).

Comment: Table 1 reflects the underlying circular logic in this approach to model testing, a logic that seems to be quite prolific in the modeling community. The performance of the models are ranked according to their deviation from the mean of the three comprehensive SCMs. Is the conclusion that the model closer to this mean is the preferable one?

Response: We have moved amended text from the supplement to the main paper to better describe the logic behind our conclusions as represented in Table 1. We do, indeed, find that – at least amongst the simple models examined – the physically based comprehensive SCMs generally respond better than more simplified models such as AR5 or FAIR. As we clarify in the revised conclusion text below, which is updated in our manuscript, this is largely a relative assessment of the responses between the SCMs, but also in comparison to more complex models where this is possible.

By using fundamental impulse tests, we found that idealized SCMs using sums of exponentials often fail to capture the responses of more complex models. SCMs that include representations of non-linear processes, such as FAIR, show improved responses, though these models still do not perform as well as comprehensive SCMs with physically-based representations. Fundamental forcing tests, such as a 4xCO_2 concentration step, show that the SCMs used here have a faster warming rate in this strong forcing regime compared to more complex models. However, comprehensive SCM responses are similar to more complex models under smaller, more realistic perturbations (Joos et al., 2013).

It is not possible to compare these fundamental responses with observations, and it is even more difficult to compare SCMs with the more complex models at decadal time horizons due to internal variability (e.g. Joos et al., 2013, Figure 2a). However, it is common in the climate modeling literature to use the multi-model mean as a base comparison. In fact, the CMIP5 multi-model mean has been shown to capture observational trends (among other climate variables) better than any individual complex model (Flato et al. 2013).

Thus, we use the comprehensive SCM multi-model mean to compare to the individual model responses for many of our experiments. We use the CMIP5 multi-model mean, developed using only those complex models with comparable climate sensitivity values to the SCMs (S9), to compare the SCM responses from a 4xCO_2 forcing step. It is our conclusion that the model response closer to the multi-model mean more accurately represent that particular response pattern. We illustrate this assumption by reporting the time-integrated temperature response percent difference from the relevant multi-model mean in Table 1 (S9).

We note that the comprehensive SCM responses to a CO_2 concentration impulse are within 2% of the comprehensive SCM average, while the idealized SCMs, FAIR v1.0 and AR5-IR, have greater differences 100 years after the pulse.

Under the 4xCO_2 concentration step experiment, we can compare the SCM responses to more complex models from CMIP5. MAGICC 6.0 appears to respond more reasonably under stronger forcing conditions than the other SCMs 100 years after those pulse, though only marginally better than FAIR. Hector v2.0 and MAGICC 5.3 have an initially quicker responses to an abrupt 4xCO2 concentration increase compared to the ESMs. AR5-IR has too strong a response to an abrupt 4xCO2 concentration increase and is insensitive to changing background concentrations.

For CH_4 emissions impulses, we use the difference from the comprehensive SCM average to rate the responses. CH_4 is a well-mixed GHG and, therefore, we expect that the climate system response to CH_4 concentration perturbations will be similar to that for CO_2. However, it would be useful to evaluate in more complex models to determine if the simple representation of chemistry in the comprehensive SCMs adequately represents the time evolution of CH_4 concentrations in response to a change in emissions.

Finally, we do not have a definitive reference for the time-dependent response to BC forcing perturbations. Instead, we compare the SCMs using the difference from the average of both MAGICC models, which both differentiate aerosol forcing between land and ocean, which results in a faster overall climate response to aerosols as compared to greenhouse gases (Shindell et al., 2014; Sand et al., 2016; Yang et al. 2018 *accepted for publication*). And in the case of BC, we note that the SCM responses should be taken critically because they do not accurately represent the temporal response to a BC step found in ESMs. A more definitive evaluation of climate system responses to aerosol perturbations would be useful. This would require additional GCM simulations to step emission changes for various aerosol species and/or forcing mechanisms. There are currently two studies that have conducted this test, one study specifically investigated NorESM's response to black carbon (BC) perturbations (Sand et al., 2016) and a more recent study that conducted similar BC perturbations in CESM (Yang et al., 2018 *accepted for publication*).

			Percent Integrated Temperature Response Differences for each Simple Climate Model (%)				
Species	**Impulse**	**Time After Pulse**	**Hector v2.0**	**MAGICC 5.3**	**MAGICC 6.0**	**FAIR v1.0**	**AR5-IR**
CO_2	4x Forcing Step	H = 100 yrs	38%	35%	15%	18%	73%
	Forcing Impulse	H = 100 yrs	1.0%	-1.2%	0.25%	-16%	23%
	GHG Emissions	H = 100 yrs	-0.57%	2.2%	-1.6%	-14%	31%
CH_4	GHG Emissions	H= 20 yrs	-3.1%	-5.6%	8.7%	--	47%
BC	Aerosol Emissions*	H = 20 yrs	-9.3%	1.1%	8.1%	--	19%

Table 2: Percent Integrated Temperature Response Differences. The values are the percentage difference in time-integrated temperature response (%) compared to the relevant reference (generally comprehensive SCM average in SI 9). * For BC specifically, we note that none of the SCMs accurately represent the temporal response for BC seen in ESMs (Sand et al., 2016) (SI12).

There are numerous benefits to using simplified models, but the selection of the model should be rooted in a clear understanding of the model responses (see Table 1). Our work illustrates the necessity of using fundamental impulse tests to evaluate SCMs and we recommend that modeling communities adopt them as a standard validation suite for any SCM. Given that idealized SCMs are biased in their response patterns, more comprehensive SCMs could be used for many applications without compromising on accessibility or computational requirements.

Changes in Manuscript: We added the majority of this response to the main paper conclusion, which more clearly explains the differences in the model responses and emphasizes the importance of conducting fundamental impulse test to evaluate SCMs.

Comment: I note, however, that the ESM responses plotted seem to be smaller than typically reported for ESMs. Some of the model runs are also present in the ensemble of Geoffroy et al., 2013, and two of them are possible to recognize in the cloud of response curves. These are the MIROC5 and GISS-E2-R. The MIROC5

run has a characteristic oscillation in the response which is easy to detect in the cloud, and GISS-E2-R is the lower curve in the cloud. For both the temperature values seem to be scaled down by a factor around 0.7 compared with the corresponding curves in Fig. 2 of Geoffroy et al., 2013. The authors should clarify this discrepancy. I notice that if the cloud is adjusted by such a factor, the comprehensive SCM curves (for ECS=3.0 degrees) in Figure 4 will appear much more centered within the range of the ESM cloud.

Response: Conducting impulse tests with complex models is computationally expensive, illustrated by the few studies employing this technique to understand the responses of models. We cite the Sand et al., 2016 study that specifically investigated NorESMs response to black carbon (BC) perturbations (Sand et al., 2016). We now include another study that conducted similar BC perturbations in CESM (Yang et al., 2018 *accepted for publication*). Other stylized CMIP5 experiments, such as the 1% CO_2 concentration experiment, are not included in our comparison because we do not consider them to be impulse response tests. It is not possible to cleanly extract the impulse response from the 1% experiments. The CMIP5 4xCO_2 concentration step experiment is mathematically related to impulse responses, so are a reasonable comparison, particularly because these are the largest suite of such tests conducted in complex models, which is the reason we highlight these results in the paper.

Geoffroy et al., 2013 reported the 4xCO_2 concentration step temperature change relative to the 150-year temperature mean from the corresponding pre-industrial control run. For comparison to the simple models, we report the drift corrected (see S3) 4xCO_2 concentration step temperature change relative to the start of the 4xCO_2 concentration run. Therefore, there will be a difference in the temperature reported. We included this additional information in the revised supplement to clarify the difference in the way modeled temperature change is reported.

Figure R3 shows the global mean temperature response from the 4xCO_2 concentration step experiment for the 20 CMIP5 models used in our comparison following the Geoffroy et al. (2013) procedure of reporting the 4xCO_2 concentration step temperature change relative to the 150-year temperature mean from the corresponding pre-industrial control run. The responses reported in Figure R3 are consistent with Geoffroy et al. (2013). We expanded the number of complex models and updated the supplementary materials accordingly.

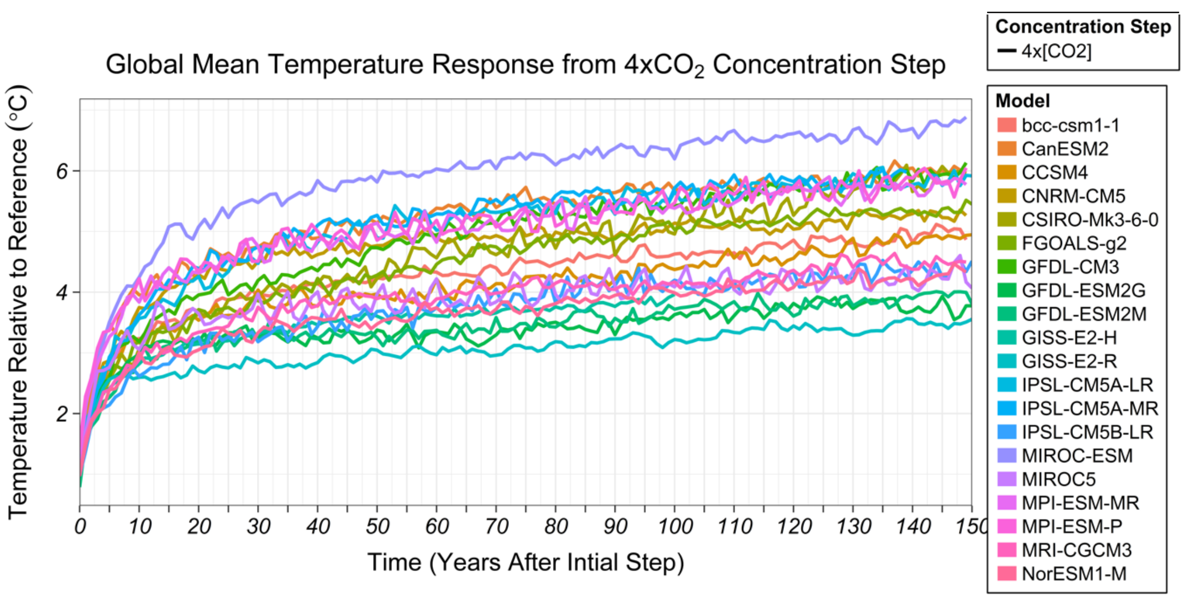

Figure R3 Global mean temperature response from 4xCO_2 concentration step in 20 CMIP5 models.

Changes in Manuscript: We added the majority of this response to the revised supplement (see S3.1).

Comment: I cannot see where it is shown in the paper that comprehensive SMCs fail to capture response timescales of ESMs to CO2 forcing. This is not apparent in Figure 4.

Response: To clarify, in Figure 4 of our manuscript the rate of temperature response from the SCMs immediately following the 4xCO_2 step is generally faster than the rate of temperature response from the ESMs. We also illustrate this in Figure S22 where we will expand the discussion in the revised manuscript, as we mentioned above. From this, we conclude that some SCMs do not capture the response timescales of ESMs.

Changes in Manuscript: None that were not already adopted.

Comment: Finally, I would urge the authors to discuss more explicitly unspoken assumptions underlying their conclusions, and also to make more explicit reference to the results from which these conclusions are drawn. For instance, in the abstract one can read:

<u>Line 17:</u> "While idealized SCMs are widely used, they fail to capture important global mean climate response features, which can produce biased temperature results."

Response: Our language was vague in the abstract and we provide revised text to more explicitly reference our results.

"We find that while idealized SCMs are widely used, they fail to capture the magnitude and timescales of global mean climate responses under emissions perturbations, which can produce biased temperature results."

Changes in Manuscript: We amended the abstract with the language in this response.

Comment: Since observations are not used in this study, the underlying assumption is that increased model complexity yields more correct results for global response features. This is not obvious. All climate models must be parametrized and constrained against observation. This means parameter fitting, and increased complexity increases the chance of overfitting. Complex models, and ESMs in particular, will to a great extent be parametrized against observations of local processes and not on the global responses. The large spread in the global responses of ESMs is a clear indication that they cannot be used as a substitute for observation of global responses.

Response: We disagree with the reviewer that the large spread in ESM global mean temperature responses means they are not useful. While some climate studies benefit from using observations, we cannot employ observations to compare with impulse response tests, as we mentioned above. As noted previously, ESMs are constrained by more detailed representations of the relevant physics (e.g. energy balance, heat transport, etc.) and the multi-model mean of ESMs does a better job of matching observations than any individual ESM. The suite of ESMs results are, therefore, one of the best (albeit not perfect by any means) tools by which we can compare SCMs.

Changes in Manuscript: None that were not already adopted.

Comment: <u>Line18:</u> "Comprehensive SCMs, which have non-linear forcing and physically-based carbon-cycle representations, show improved responses compared to idealized SCMs."

Again, a simple model fitted to observation can represent reality better than a more complex model fitted to observation, because overfitting of a complex model may weight real physical processes in an unrealistic manner.

Response: While it is true that a simple model may fit observations better than a more complex model, we do not agree that this is an indication that the fit represents a better representation of reality. This may also mean that, due to a lack of physical constraints in an overly simplified model, a good fit is obtained for the wrong reasons. We again point out the long-standing finding that the multi-model mean for CMIP-class models better represents reality as compared to any individual model. This finding indicates that the physical processes represented in these models (some explicit, some parameterized) are providing meaningful constraints on the behavior of the coupled system.

In our experience, the overall results of these global models, such as global temperature change, are not fitted to observational datasets. Instead, individual components are developed and tested against appropriate observations (e.g., top of atmosphere radiative flux, cloud properties, laboratory measurements, etc.), which provides an emergent, aggregate model behavior (albeit, dependent on the properties of these numerous sub-systems.). Every GCM is wrong, at least in some specific aspects, but the evidence suggests that the behavior of these models taken together is a useful overall constraint on Earth system responses (Flato et al. 2013).

These impulse response tests allow us to determine the underlying dynamics of SCMs so as to better elucidate any potential issues with later analysis using these models. For example, a SCM with a faster overall temperature response to a forcing would return a different implied value of any fitting parameters (such as climate sensitivity) than a model with a slower fundamental response.

Changes in Manuscript: None that were not already adopted.

Comment: Line 20: "Even some comprehensive SCMs fail to capture response time scales of more complex models under BC or CO2 forcing perturbations."

The BC case may be true, but is based on one single simulation in NorESM.

Response: There are now two studies that have conducted a BC emissions impulse in complex models (i.e., Sand et al., 2016 and Yang et al., 2018) and cited them above. We noted above that the Sand et al., 2016 study specifically investigated NorESMs response to black carbon (BC) perturbations (Sand et al., 2016), while another conducted similar BC perturbations in CESM (Yang et al., 2018). Further, Shindell et al. (2014) concluded that without accounting for regional warming and feedbacks, simple models can mis-represent the timescale for aerosol impacts, though we note that some models such as MAGICC 5.3 and MAGICC 6.0 do have differential land-ocean and North-South hemisphere forcing that better represent the response of the climate system to aerosols (Smith et al., 2014).

Changes in Manuscript: We amended the manuscript and supplement to include references to the literature exploring model responses to black carbon.

Comment: Line 21: "These results suggest where improvements should be made to SCMs."
It would be very helpful if explicit improvements were suggested.

Response: We avoided adding explicit suggestions on areas where SCMs could be improved because modeling groups have a variety of reasons for implementing different features and components in their models. We stated in our manuscript that "Given that idealized SCMs are biased in their response patterns, more comprehensive SCMs could be used for many applications without compromising on accessibility or computational requirements." Some modeling groups favor answering certain scientific questions versus flexibility versus computational intensity differently, for instance, and the purpose of our paper is to explore mechanism for assessing those differences to inform users. Nonetheless, we expanded the conclusion in our response to more fully discuss the scale used Table 1 and we believe this expanded discussion suggests areas of improvement.

Changes in Manuscript: We amended the conclusion accordingly.

Comment: The reference to Chapter 8 in IPCC AR5 WG3 (Myhre et al., 2013) for a description is not very user friendly. It took me a lot of time to identify the relevant part of that chapter and the corresponding Supplement.

Response: We have added additional details in our citations of Chapter 8 in the IPCC AR5 for clarity. The manuscript and supplement have been updated.

Changes in Manuscript: We amended the manuscript and supplement accordingly.

Comment: In the main manuscript reference to sections, tables, and figures in the supplement are named SI1 etc., while in the supplement itself they are referred to as S1 etc. Be consistent.

Response: Thank you for identifying this error. We have updated the manuscript to be consistent with the supplement.

Changes in Manuscript: We amended the manuscript and supplement accordingly.

Comment: On pages 58 and 61 in the supplement is referred to Figure 5 in the main paper. This figure does not exist.

Response: Thank you for identifying this error. The reference should be to Figure 4, and we apologize for any confusion this might have caused. The supplement has been updated.

Changes in Manuscript: We amended the supplement accordingly.

Citations from Response to Reviewer #1

Flato, G., Marotzke, J., Abiodun, B., Braconnot, P., Chou, S. C., Collins, W., Cox, P., Driouech, F., Emori, S., Eyring, V., Forest, C., Gleckler, P., Guilyardi, E., Jakob, C., Kattsov, V., Reason, C. and Rummukainen, M.: Evaluation of Climate Models, Clim. Chang. 2013 Phys. Sci. Basis. Contrib. Work. Gr. I to Fifth Assess. Rep. Intergov. Panel Clim. Chang., 741–866, doi:10.1017/CBO9781107415324, 2013.
Friedlingstein, P., Meinshausen, M., Arora, V. K., Jones, C. D., Anav, A., Liddicoat, S. K. and Knutti, R.: Uncertainties in CMIP5 climate projections due to carbon cycle feedbacks, J. Clim., 27(2), 511–526, doi:10.1175/JCLI-D-12-00579.1, 2014.

Geoffroy, O., Saint-martin, D., Olivié, D. J. L., Voldoire, A., Bellon, G. and Tytéca, S.: Transient climate response in a two-layer energy-balance model. Part I: Analytical solution and parameter calibration using CMIP5 AOGCM experiments, J. Clim., 26(6), 1841–1857, doi:10.1175/JCLI-D-12-00195.1, 2013.

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Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T. and Zhang, H.: Anthropogenic and Natural Radiative Forcing, Clim. Chang. 2013 Phys. Sci. Basis. Contrib. Work. Gr. I to Fifth Assess. Rep. Intergov. Panel Clim. Chang., 659–740, doi:10.1017/ CBO9781107415324.018, 2013.

Sand, M., Berntsen, T. K., Von Salzen, K., Flanner, M. G., Langner, J. and Victor, D. G.: Response of Arctic temperature to changes in emissions of short-lived climate forcers, Nat. Clim. Chang., 6(3), 286–289, doi:10.1038/nclimate2880, 2016.

Smith, S. J., Wigley, T. M. L., Meinshausen, M. & Rogelj, J. 2014. Questions of bias in climate models. Nature Clim. Change, **4**, 741-742. doi: 10.1038/nclimate2345

Shindell, Drew T. 2014. "Inhomogeneous Forcing and Transient Climate Sensitivity." *Nature Climate Change* 4(4): 18–21.

Yang, Y., Wang, H., Smith, S. J., Ma, P. L., & Rasch, P. J. 2018. Source attribution of black carbon and its direct radiative forcing in China. *Atmospheric Chemistry & Physics*, *17*(6).

Reply to Reviewer #2

Comment: SCMs are routinely used to emulate state of the art GCMs, and generally display reasonable (though not perfect) agreement when tuned specifically to do so. The authors themselves cite several papers relating to this which discuss strengths and weaknesses of such emulation. While of course SCMs can also be integrated with standard (default) parameter values to provide some guidance as to how the climate system may behave, these simulation will not encapsulate our uncertainty in the best parameter values to use. Furthermore, such simulations will depend greatly on how the default parameter values were chosen, which may differ between SCMs.

Response: The aim of this paper is not to validate any individual simple climate model (SCM), nor the range of parameters used in the SCMs, which are also explored in the literature cited in our manuscript as you note. Rather, we are evaluating the fundamental behavior of the simple models. However, we do agree that understanding the uncertainty associated with our results is important and based on the comments here and from Reviewer #1, we have now included the parameter files in the supplement so show the default parameters of the models.

In our original supplement we conducted a simple sensitivity test for the 4xCO_2 concentration step experiment by changing the climate sensitivity values in the three comprehensive SCMs used in this paper. Based on your concerns, we have added some additional tests to the supplement of our paper by exploring a range of climate sensitivity values and ocean diffusivity values in MAGICC 6.0 under a unit pulse of CO_2 emissions and a unit pulse of CO_2 concentration.

We selected climate sensitivity and ocean diffusivity values from the parameter ranges presented in Table 1B in Meinshausen et al., 2011. The values are the native MAGICC 6.0 parameters required to emulate complex models used in CMIP3 using three calibrated parameters (climate sensitivity, ocean diffusivity, and land/ocean warming). We provided the climate sensitivity and ocean diffusivity value ranges we explored in Table R2 below.

Table R2 MAGICC 6.0 parameter values from Meinshausen et al., 2011 Table 1B for sensitivity tests

Scenario	Climate sensitivity (K)	Ocean diffusivity ($cm^2 s^{-1}$)
Base Case	3.0	1.1
High Ocean diffusivity	3.0	3.74
Low Ocean diffusivity	3.0	0.50
High Climate sensitivity	6.03	1.1
Low Climate sensitivity	1.94	1.1

Figure R4 shows the global mean temperature response exploring the range of ocean diffusivity (Kz) (a) and global mean temperature response exploring the range of climate sensitivity (CS) (b) under a CO_2 emissions perturbation. Figure R5 shows the same results for under a CO_2 concentration pulse. Both figures illustrate that climate sensitivity has the greatest impact on the responses and in our manuscript, we accounted for this and used similar climate sensitivity values in SCMs where possible, unless otherwise noted in the supplemental figures.

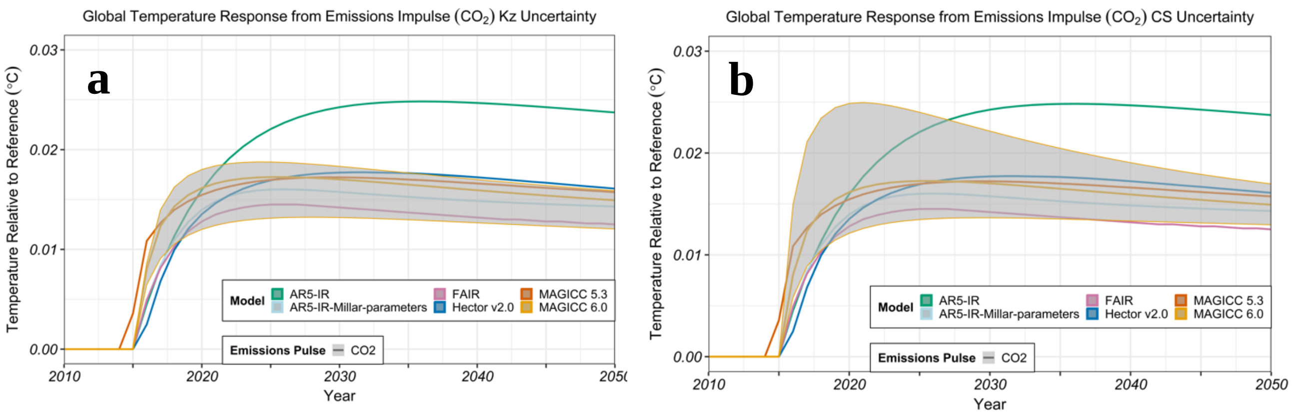

Figure R4 Global mean temperature response exploring the range of ocean diffusivity (Kz) (a) and Global mean temperature response exploring the range of climate sensitivity (CS) (b) from a CO_2 emissions perturbation in SCMs (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, AR5-IR – green, FAIR –pink, AR5-IR-Millar-parameters –light blue). The grey shaded region in each figure shows the range in MAGICC 6.0 responses found using the Table R2 parameters. We note that the range of responses exploring CS (b) are normalized to account for the different climate conditions under difference CS values.

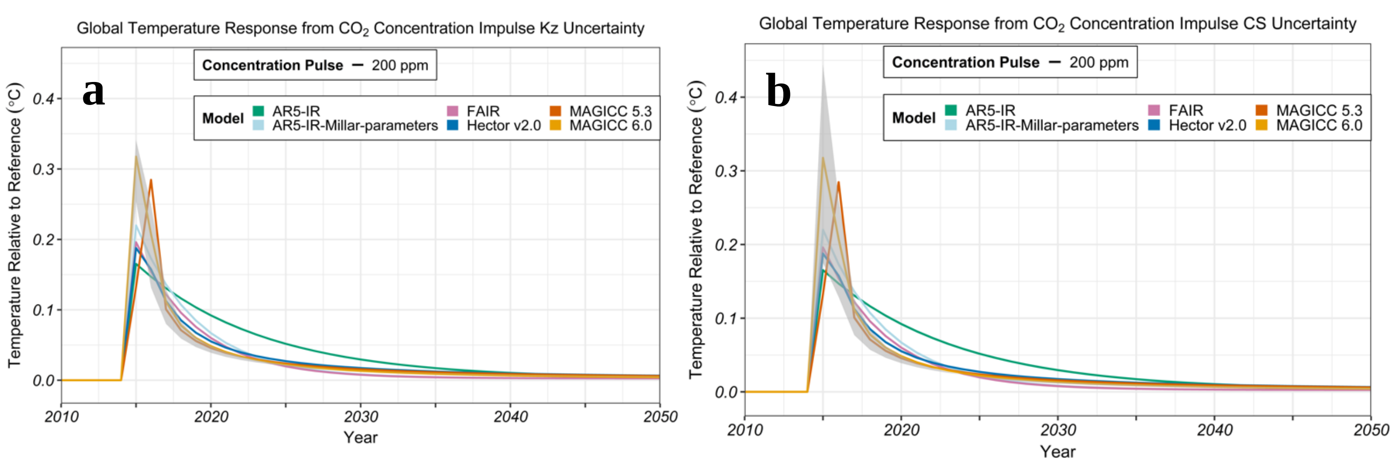

Figure R5 Global mean temperature response exploring the range of ocean diffusivity (Kz) (a) and Global mean temperature response exploring the range of climate sensitivity (CS) (b) from a CO_2 concentration pulse in SCMs (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, AR5-IR – green, FAIR –pink, AR5-IR-Millar-parameters –light blue). The grey shaded region in each figure shows the range in MAGICC 6.0 responses found using the Table R2 parameters. We note that the range of responses exploring CS (b) are normalized to account for the different climate conditions difference CS values.

We acknowledge, however, that vertical ocean diffusivity has a large impact on ocean heat uptake and we do note that this parameter selection also impacts the responses in the SCMs, particular under a CO_2 emissions pulse (Meinshausen et al., 2011). However, the SCMs we compare in our paper either do not have the same definitions of vertical ocean diffusivity, as is the case for the comprehensive SCMs, or ocean diffusivity is not directly represented in the models, as is the case for idealized SCMs. For our purposes, therefore, we kept the ocean diffusivity values at their default values within the comprehensive SCMs. By exploring the uncertainty in ocean diffusivity, we have, in fact, bolstered the main conclusions of our manuscript.

For completeness we also acknowledge that Meinshausen et al., 2011 spanned ranges of land/ocean warming contrast (RLO) in the three-parameter calibration described in Table 1B of their manuscript. And again, the SCMs either use the same values of RLO, as is the case for both versions of MAGICC, or this parameter is not represented in the idealized models. In fact, from our work using impulse response test to characterize SCMs, we concluded that SCMs without differential warming do not correctly capture the response pattern to BC perturbations.

Changes in Manuscript: We added this response in its entirety to the revised supplement (see S11.2).

Comment: Given that the GCMs disagree substantially amongst themselves, I do not understand the purpose of this paper in comparing the outputs of standard SCM instances to themselves and GCM output. It is inevitable that these will not match closely when the SCM parameters are set to standard values, and I do not think it is straightforward to attribute such differences to structural limitations of the SCMs without first checking that they cannot be explained by parameter choices.

Response: We remind the reviewer that we are not attempting to emulate GCMs in our paper. Instead, we evaluate SCM responses by comparing the models to themselves and also, in the limited cases where this is possible, to more complex models.

One key purpose of this paper is to determine the fundamental response of these models by conducting impulse response tests (as recommended, for example, by a recent report by the NAS). This has not been done before, and this alone provides useful information on the behavior of these models, how this differs between the models, and the magnitude of those differences. Given the extremely widespread use of these models, this is a critical task.

We go beyond just comparing these models to each other, by comparing against the suite of complex model results were this is possible. We do this because it has been shown that the multi-model mean behavior of the complex models replicates well a broad suite of observations (e.g., Figure 9.7, Flato et al. 2013). Further, comparing simple models to complex models is a common technique employed in the literature (e.g., Joos et al., 2013). For example, in the abrupt 4 X CO2 regime, we find that the SCMs as a group initially respond more quickly than the GCMs. We conclude from this that there must be some physical processes represented in the GCMs that buffers the initial response in this regime that is lacking in the SCMs.

From our exploration of the range of ocean diffusivity values and climate sensitivity values above, we have found that the response differences we noted in our conclusions cannot be explained by parameter choice alone. We appreciate that the reviewer brought up this important question, and we will amend our paper discussion based on these results but note that our main conclusions remain. In fact, we believe that illustrating the ranges in responses further bolsters our claim that impulse response tests are needed to fully understand model behavior.

Changes in Manuscript: We amended the manuscript to clarify the purpose of our paper and better articulates the potential impact of our work, referencing the National Academies for example. We used text from this response in the manuscript.

Comment: Of course in the simplest of cases one might show that a complex curve output by a sophisticated SCM/GCM simply cannot be explained by a very simple parametric form, but even here it would be appropriate to explore how close a fit could be obtained.

Response: Fitting individual simple models to more complex models is generally explored by the individual SCM development teams, and we cite papers from the Hector, MAGICC, and FAIR model development teams which explore their respective model's ability to fit a GCM (or the multi-model mean) with a given set of parameters. While emulation is outside the scope of this paper, but to address the reviewer's comments, above we have expanded our impulse tests to include an uncertainty test which relies on parameters derived from GCM emulation experiments using MAGICC 6.0. We will also add a discussion of fitting SCMs to more complex models to the paper to address the points raised by the reviewer.

Changes in Manuscript: We addressed the sensitivity experiment in S11.2.

Comment: One could reasonably compare SCM responses amongst themselves when tuned to each other or to some common target (either observational or GCM-based). However, this has not been performed here. While in some experiments the sensitivity parameter has been set to a common value of 3, other model parameters appear to differ between the SCMS and were apparently set to standard values which were probably chosen by the SCM authors for a variety of reasons. Thus it is not possible to determine how much of the differences in response are due to model structure, and how much is the result of using different parameter values/tuning strategies.

Response: We remind the reviewer that the goal of our paper is to evaluate the SCMs, as we mentioned above, and we ultimately suggest a suite of fundamental impulse-response tests using realistic backgrounds for use in SCM development. We make this clearer in our revised manuscript by including some of the text mentioned above, such as:

"In our paper, we evaluated the SCMs by comparing the models to themselves and also, in the limited cases where this is possible, to more complex models. We compare against the suite of complex model results because it has been shown that the multi-model mean behavior of the complex models replicates well a broad suite of observations (e.g., Figure 9.7, Flato et al. 2013)."

The sensitivity tests we have added to the paper do provide useful general information on how parameter choices might influence model responses, which addresses part of the question posed above. (We note also, that in response to reviewer 1, we have also added an example of how the idealized AR5 model response changes with a change in parameters.) Our text will be amended to reflect these results. However, as we noted above, due to structural differences in the SCMs it is, in general, not possible to operate the models with identical parameter values. This reinforces the importance of conducting fundamental impulse response tests to quantify the behavior of the SCMs.

Changes in Manuscript: We addressed the sensitivity experiment in S11.2 and amended the text as stated.

Comment: I would also question whether the relatively unrealistic abrupt tests are a useful diagnostic tool for the model behaviour. While I accept it can be interesting to characterise the response to idealised forcing scenarios, it may be that the differences are much less significant when more realistic scenarios are applied, and the authors acknowledge this point in their conclusions.

Response: There is a long history of doing just such idealized, abrupt tests to evaluate model behavior. The CMIP5 4xCO_2 concentration step experiments are the largest suite of impulse response tests conducted in complex models, for example, which is the reason we highlight these results in the paper.

The impulse response tests conducted enable us to uncover differences in model behavior that are not apparent when running standard, multi-emission scenarios. Indeed, one of the important uses of SCMs is to conduct model experiments were there may be relatively small changes in emissions between two scenarios. Because SCMs do not exhibit internal variability, such experiments can be used to quantify such changes. Impulse response tests also allow us to understand, on a more fundamental level, differences between SCMs that have been found comparing simulations with more conventional scenarios (e.g., van Vuuren et al., 2011).

Changes in Manuscript: None that were not already adopted.

Comment: Thus, this analysis does not sufficiently advance our understanding of the behaviour of SCMs, and I am sorry to say that I cannot support publication of this manuscript in ESD.

Response: We believe this paper does present novel and useful results that are new to the literature. Though fundamental impulse tests have been used a few times in the literature in this context, our manuscript employs these existing techniques in a new manner. This is the first study in the literature to rigorously evaluate SCMs using impulse-response tests. SCMs are widely used in the literature and in decision-making context, e.g., within Intergovernmental Panel on Climate Change (IPCC) Reports, coupled with Integrated Assessment Models. In fact, a paper describing a commonly used SCM, MAGICC 6.0, has been cited 371 times in the literature and policy contexts. Another model, the impulse response model used in the IPCC Fifth Assessment Report (AR5-IR), is heavily used by the scientific community to support decision making. Despite their importance, the fundamental responses of SCMs are not fully characterized. The U.S. National Academies of Science (2016) specifically suggested that SCMs be, “assessed on the basis of [the] response to a pulse of emissions,” which we do here. Additionally, we provide a set of tests that we recommend as a standard evaluation suite for any SCM.

Changes in Manuscript: We added some text from this response to the amended manuscript, such as citing the National Academies and clarifying that our manuscript employs existing techniques in a new manner.

Comment: As a minor comment, the "unit testing" terminology seems inappropriate, the test here is rather more comprehensive than such a term usually implies, and furthermore there does not appear to be any clear criteria for success or failure.

Response: We received several comments on our use of the phrase “unit testing”. Though we believe our use of the phrase is consistent with its use in software, as we replied to the Short Comment and Reviewer #1, we will update the language to “fundamental impulse tests” to avoid confusion.

Changes in Manuscript: None that were not already adopted based on Reviewer #1.

Citations from Response to Reviewer #2

Flato, G., Marotzke, J., Abiodun, B., Braconnot, P., Chou, S. C., Collins, W., Cox, P., Driouech, F., Emori, S., Eyring, V., Forest, C., Gleckler, P., Guilyardi, E., Jakob, C., Kattsov, V., Reason, C. and Rummukainen, M.: Evaluation of Climate Models, Clim. Chang. 2013 Phys. Sci. Basis. Contrib. Work. Gr. I to Fifth Assess. Rep. Intergov. Panel Clim. Chang., 741–866, doi:10.1017/CBO9781107415324, 2013.

Friedlingstein, P., Meinshausen, M., Arora, V. K., Jones, C. D., Anav, A., Liddicoat, S. K. and Knutti, R.: Uncertainties in CMIP5 climate projections due to carbon cycle feedbacks, J. Clim., 27(2), 511–526, doi:10.1175/JCLI-D-12-00579.1, 2014.

Joos, F., Roth, R., Fuglestvedt, J. S., Peters, G. P., Enting, I. G., Von Bloh, W., Brovkin, V., Burke, E. J., Eby, M., Edwards, N. R., Friedrich, T., Frölicher, T. L., Halloran, P. R., Holden, P. B., Jones, C., Kleinen, T., Mackenzie, F. T., Matsumoto, K., Meinshausen, M., Plattner, G. K., Reisinger, A., Segschneider, J., Shaffer, G., Steinacher, M., Strassmann, K., Tanaka, K., Timmermann, A. and Weaver, A. J.: Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: A multi-model analysis, Atmos. Chem. Phys., 13(5), 2793–2825, doi:10.5194/acp-13-2793-2013, 2013.

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Evaluating Climate Emulation: Fundamental Impulse~~Unit~~ Testing of Simple Climate Models

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Abstract. Simple climate models (SCMs) are numerical representations of the Earth's gas cycles and climate system. SCMs are easy to use and computationally inexpensive, making them an ideal tool in both scientific and decision-making contexts (e.g., complex climate model emulation; parameter estimation experiments; climate metric calculations; and probabilistic analyses). Despite their prolific use, the fundamental responses of SCMs are often not directly characterized. In this study, we use fundamental impulse~~unit~~ tests of three chemical species (CO_2, CH_4, and BC) to understand the fundamental gas cycle and climate system responses of several comprehensive~~SCMs~~ (Hector v2.0, MAGICC 5.3, MAGICC 6.0) and idealized (~~,~~FAIR v1.0, ~~and~~ AR5-IR) SCMs.~~).~~ We find that while idealized SCMs are widely used, they fail to capture the magnitude and timescales of~~important~~ global mean climate responses under emissions perturbations~~response features~~, which can produce biased temperature results. Comprehensive SCMs, which have non-linear forcing and physically-based carbon cycle representations, show improved responses compared to idealized SCMs. Even some comprehensive SCMs fail to capture response timescales of more complex models under BC or CO_2 forcing perturbations. These results suggest where improvements should be made to SCMs. Further, we provide a set of fundamental tests that we recommend as a standard validation suite for any SCM. Fundamental impulse~~Unit~~ tests allow users to understand differences in model responses and the impact of model selection on results.

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1 Introduction

Climate models are one of the primary tools used by interdisciplinary scientists to understand changes in the climate. Models are generally classified by their complexity and comprehensiveness, spanning a range from idealized simple climate models (SCMs) to complex coupled Earth System Models (ESMs). While ESMs run on supercomputers and can take several months to simulate 100 years, SCMs can simulate the same period on a personal computer in seconds (van Vuuren et al., 2011a). SCMs have less detailed representations than ESMs, and themselves range in structure from idealized to more comprehensive climate representations (Millar et al., 2017). Comprehensive SCMs are models rooted in physical processes (e.g.,~~.~~ energy balance models) and capture the main pathway by which climate forcers alter the energy budget: emissions to concentrations, top-of-the~~-~~atmosphere radiative forcing, and global mean surface air temperature (Geoffroy et al., 2013; Hartin et al., 2015; Meinshausen et al., 2011; Tanaka and Kriegler, 2007). Idealized SCMs use even fewer equations, which do not necessarily correspond to individual physical processes, to parametrically represent the climate system (Millar et al., 2017).

SCMs are widely used in scientific and decision-making contexts largely because of their advantageous features, including their ease of use and low computational intensiveness. In particular, SCMs are traditionally used within human-Earth system models. These models couple the climate system with representations of the dynamics within the human system (e.g., energy systems and land-use changes) (Hartin et al., 2015; Ortiz and Markandya, 2009; S.H. Schneider and S.L. Thompson, 2000; Strassmann and Joos, 2018) and are used to assess global forcing or temperature targets (e.g., Representative Concentration Pathways (van Vuuren et al., 2011b), Shared Socioeconomic Pathways (Moss et al., 2010)). Several studies investigated potential sources of human-Earth system model uncertainty by exploring the climate components driving the models (Calel and Stainforth, 2017; Harmsen et al., 2015; van Vuuren et al., 2008, 2011a). Van Vuuren et al. (2011a) concluded that in most cases the results from human-Earth system models and SCMs were similar to the more complex, coupled Earth System Models (ESMs). The authors further noted that differences in SCM results can have implications for decision makers informed by such results, illustrating the need for improvements in uncertainty analysis (e.g.,~~.~~ carbon cycle feedbacks)~~. or inertia in climate response).~~ Harmsen et al. (2015) extended van Vuuren's analysis to investigate emission reduction scenarios by including non-CO_2 radiative forcing. The authors concluded that many models may underestimate forcing differences after applying emission reduction scenarios, due to the omission of important short-lived climate forcers, such as black carbon (BC).

Few studies utilize idealized SCMs in human-Earth system models because of their inability to represent nonlinear forcings, such as air-sea exchanges (Khodayari et al., 2013) or ocean chemistry (Hooss et al., 2001; Tanaka and Kriegler, 2007). With simple extensions of the carbon cycle (e.g., ocean carbonate chemistry), both Hoos et al. (2001) and Tanaka and Kriegler (2007) found improved responses from their respective impulse response models, applicable when coupling to human-Earth system models.

Comprehensive SCMs are also used to simulate the climate or carbon cycle (Friedlingstein et al., 2014; Joos et al., 1999; Knutti et al., 2008), explore responses to anthropogenic perturbations (Geoffroy et al., 2013; Hope, 2006; Meinshausen et al., 2009; Rogelj et al., 2014), or address model spread in the various model intercomparison projects (MIPs) (Knutti and Sedláček, 2012; Monckton et al., 2015; Rogelj et al., 2012). These analyses often include comparisons to more complex models (Meinshausen et al., 2008, 2011). One comprehensive~~comprehsive~~ SCM in particular, MAGICC 6.0, is used as a reference in many studies because of its well-documented ability~~abilitiy~~ to emulate complex models (e.g., van Vuuren et al., 2011a).

Similarly, individual idealized SCM developers also explore the ability of impulse-response functions to simulate climate or carbon-cycle responses to perturbations (Hooss et al., 2001; Millar et al., 2016; Sausen and Schumann, 2000; Strassmann and Joos, 2018; Thompson and Randerson, 1999), often comparing to more complex models (Joos and Bruno, 1996). Sand et al. (2016), for example, employed an idealized~~a stylized~~ SCM using sums of exponentials (AR5-IR) to find the Arctic temperature response to regional short-lived climate forcer emissions (e.g., BC)~~),~~ and compared these responses to more complex models.

Climate indicators, such as transient climate response (TCR) (Allen et al., 2018; Millar et al., 2017), can~~are~~ also be informed~~calculated~~ using SCMs. TCR is the measure of the climate response to a 1% yr^{-1} increase in CO_2 concentration until doubling of CO_2 relative to pre-industrial level. TCR is useful for understanding the climate response on shorter time scales, as CO_2 concentration doubling takes place in 70 years, a time-frame relevant for many planning decisions (Flato et al., 2013; Millar et al., 2015). TCR and~~Used in combination with TCR,~~ the equilibrium climate sensitivity (ECS) can be combined to estimate~~also be used to attribute the fraction of observed warming to anthropogenic influences, called~~ the realized warming fraction (RWF), the fraction of total warming manifested up to a given time.~~).~~ Millar et al. (2015) investigated TCR and ECS within an~~a global climate-calibrated~~ impulse-response model to show the implications of these values on future climate projections by specifically looking at the RWF.

Sums of exponentials are also commonly used to calculate other climate metrics, such as the global warming potential (GWP) and global temperature potential (GTP) (Aamaas et al., 2013; Berntsen and Fuglestvedt, 2008; Fuglestvedt et al., 2010; Peters et al., 2011; Sarofim and Giordano, 2018). Idealized~~Stylized~~ SCMs, however, often do not account for carbon cycle feedbacks, important for more realistic representations of climate. Both Millar et al. (2017) and Gasser et al. (2017) investigated the effects of adding carbon cycle feedbacks on these metrics produced with idealized~~stylized~~ SCMs, and found that accounting for feedbacks improved model responses (at least modestly, Gasser et al. 2017).

Despite their importance and wide use, the fundamental responses of SCMs have not been fully characterized (Thompson, 2018). In this paper, we use impulse-response tests to address this gap.

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2 Methods

2.1 Fundamental impulse ~~Unit~~ tests. Impulse~~We use impulse~~-response tests~~, a type of unit test, to address this gap as recently suggested by the US National Academies (National Academies of Sciences, Engineering, 2016).~~ characterize~~An impulse-response test characterizes~~ the SCMs' climate and gas-cycle response to a forcing or emission impulse (Good et al., 2011; Joos et al., 2013). Though fundamental impulse tests have been used in the literature (e.g., Joos et al., 2013),~~Here,~~ we employ these existing techniques to evaluate~~take a comprehensive approach evaluating~~ several SCMs. In fact, the U.S. National Academies of Science (2016) specifically suggested that SCMs be "assessed on the basis of [the] response to a pulse of emissions," which we do here ~~using~~ (National Academies of Sciences, Engineering, 2016).

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We use three main forcing and emission impulse tests to understand the response of the climate system and gas cycles in the models~~. We use three main impulse tests~~: (a) a concentration impulse of CO_2, (b) emissions impulses of BC,

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CH_4, or CO_2, (c) a 4×CO_2 step increase in CO_2 concentration. We carry out these experiments by instantaneously increasing emissions or forcing values in 2015 to avoid the model base years of our SCMs (see S1). ~~SI1).~~

We note that impulse-response tests can be considered a type of unit test. Unit testing in software refers to a specific method of comparing output from the smallest portion of code, called a unit (i.e., function), to known outputs (Clune and Rood 2011). Here, we use this term in a similar way as van Vuuren et al. (2011), where MAGICC 6.0 was used as the reference output to compare several human-Earth system models. We conduct our tests with comparable inputs, which are provided in the Supplementary Materials, and compare model-generated outputs from several SCMs.

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2.2 Background concentrations.~~.~~ Our impulse response~~unit~~ tests are conducted against a time-changing greenhouse gas (GHG)~~CO_2~~ concentration background using emissions from the Representative Concentration Pathway (RCP) 4.5 scenario (Thomson et al., 2011). For each~~ unit~~ test, therefore, we run a reference scenario in the SCMs, followed by each perturbation case.~~ described above.~~ We report the response, which is obtained by subtracting the reference from the perturbation results for each model. A~~. The~~ changing GHG background ~~CO_2~~ concentration ~~background~~ is a more realistic scenario overall and also reveals biases not otherwise apparent under constant concentration conditions, for example, in SCMs insensitive to changing background concentrations. Further, for emissions impulses this methodology is more readily implemented as a standard impulse~~unit~~ test (see S1~~SI1~~), as we recommend below. Conducting tests against a constant concentration background in any but the most idealized SCM requires an inversion calculation to determine the emissions pathway that results in a constant concentration. This is an unnecessary barrier to conducting routine impulse response tests.

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2.3 Models. Three comprehensive SCMs—Hector v2.0 (Hartin et al., 2015; Kriegler, 2005), MAGICC 5.3 BC-OC (Smith and Bond, 2014), and MAGICC 6.0 (Meinshausen et al., 2011)—are used in this study (S2~~SI2~~). The models were selected based on their availability, use in the literature, and their applicability to decision making. We also include two idealized SCMs which employ sums of exponentials to represent the climate or gas-cycle responses, a general approach often used in the literature (Aamaas et al., 2013; Fuglestvedt et al., 2003), referred to as impulse response functions (IRFs). IRFs linearly approximate the response of a system to a given forcing (Hooss et al., 2001). A widely used version tested here is the impulse response (IR) model used in the Intergovernmental Panel on Climate Change Fifth Assessment Report (Myhre et al., 2013), referred to here as AR5-IR. Additionally, we test version 1.0 of the~~ ~~ Finite Amplitude IR (FAIR) model, an extension of AR5-IR including a representation of carbon cycle feedbacks and non-linear forcing (Millar et al., 2017).

2.2 Parameter selection. We are testing the model responses as they would be 'out of the box' and only make modifications if required for the models to run. A model's ability to emulate an ESM or the multi-model ESM mean is generally explored by the individual SCM development teams, as noted in the references for the Hector, MAGICC, and FAIR models. While emulation is outside the scope of this paper, we conduct sensitivity tests by relying on parameters derived from ESM emulation experiments using MAGICC 6.0 (see S11). We note that due to structural differences in the SCMs it is, in general, not possible to operate the models with identical parameter values (see S2). This reinforces the importance of conducting fundamental impulse response tests to quantify the behavior of the SCMs.

3 Results

In our paper, we evaluated the SCMs by comparing the models to each other and also, in the limited cases where this is possible, to more complex models. We compare against the suite of complex model results because it has been shown that the multi-model mean behavior of the complex models replicates well a broad suite of observations (e.g., Figure 9.7, Flato et al. 2013). We highlight differences in model responses to a suite of impulse~~unit~~ tests to support an informed model selection (see Table 1).

We begin by testing the fundamental dynamics of the temperature response to a well-mixed greenhouse gas forcing impulse by perturbing CO_2 concentrations (Fig. 1), bypassing the carbon cycle (if present).

We report both time-series responses (Fig. 1a) and time-integrated responses (Fig. 1b; SI 9). Integrated responses form the basis of commonly used metrics, such as GWP and GTP (Fuglestvedt et al., 2010).

3.1 Responses to CO_2 Concentration Impulse. First, we consider the comprehensive SCMs. Both versions of MAGICC show shifted responses in the first few years following the perturbation due to the way this model treats sub-annual integration of forcing (S5~~SI5~~). The shifted responses do not significantly impact integrated results. MAGICC 6.0 initially responds more strongly to the perturbation, with a 6% larger integrated temperature response 20 years after the impulse compared to the comprehensive SCM~~SCMs~~ average (S9~~SI9~~). After 30 years, the comprehensive SCMs are within 2% of each other.

The idealized SCMs show varied responses to a CO_2 concentration impulse. Differences in the AR5-IR and FAIR responses are due to a nonlinearity also present in FAIR. According to Equation 8 in Millar et al. (2017) FAIR will have a differential response to changing background CO_2 concentrations. By contrast, AR5-IR parameterizes the climate response to a unit forcing using a sum of exponentials as given by Equation 8.SM.13 in Myhre et al. (2013).

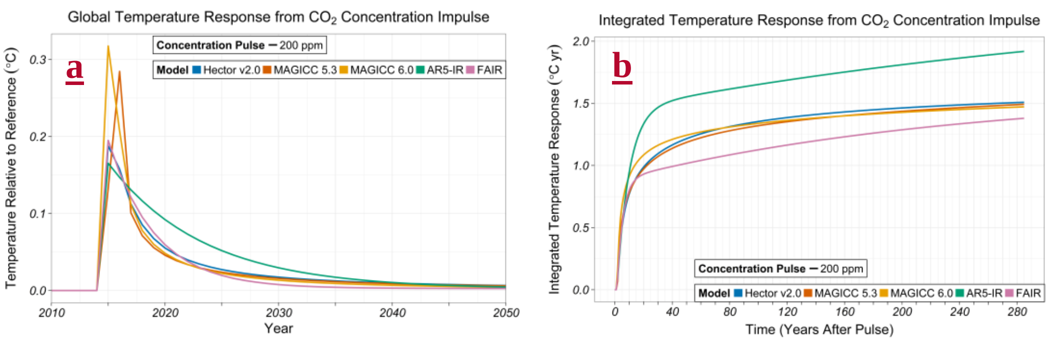

Figure 1: Global mean temperature response (a) and integrated global mean temperature response (b) from a CO_2 concentration perturbation in SCMs (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, AR5-IR – green, FAIR –pink). The perturbations are conducted in 2015 against the background of the Representative Concentration Pathway (RCP) 4.5 scenario (see Methods). The time-integrated response, analogous to the Absolute Global Temperature Potential, is reported as 0-285 years after the perturbation.

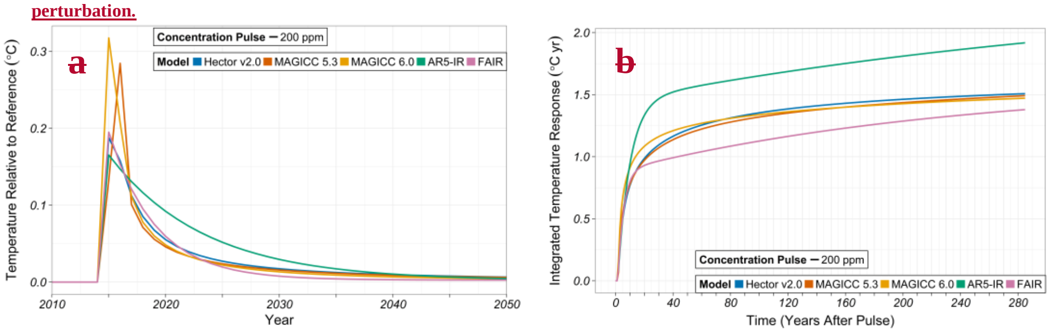

Figure 1: Global mean temperature response (a) and integrated global mean temperature response (b) from a CO_2 concentration perturbation in SCMs (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, AR5-IR – green, FAIR –pink). The perturbations are conducted in 2015 against the background of the Representative Concentration Pathway (RCP) 4.5 scenario (see Methods). The time-integrated response, analogous to the Absolute Global Temperature Potential, is reported as 0-285 years after the perturbation.

AR5-IR has a much stronger response compared to the comprehensive SCMs; the integrated response is 6% larger than the comprehensive SCMs 20 years after the pulse, increasing to 30% by the end of the model runs. This large difference is due to the absence of feedbacks and nonlinearities in the AR-IR model. FAIR contains an approximate representation of theseFAIR represents such nonlinearities, responding similarly to the comprehensive SCMs in the near-term, but has a 7% weaker integrated response 285 years after the impulse. The approximations used to represent the carbon cycle and non-linear forcing might account for this, but it is unclear from these results.

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3.2 Responses to Emissions Impulses. We now test the model response to an emissions impulse. Compared to forcing-only experiments, emissions perturbation experiments have additional levels of uncertainty from the conversion of emissions to concentrations, as well as carbon cycle feedbacks. As a diagnostic we examine the forcing response, functionally equivalent to examining the concentration response. The three comprehensive SCMs have small differences (<10%) in the integrated forcing response (Fig. 2b) from CO_2 (dashed) emission impulses for all time horizons. AR5-IR, an idealized SCM, responds 11% stronger than the comprehensive SCMs average 20 years after the pulse, increasing to a 17% difference in~~285 years after~~ the integrated response 285 years after the impulse. FAIR does not calculate concentration or forcing, so cannot be included in these comparisons.~~impulse.~~

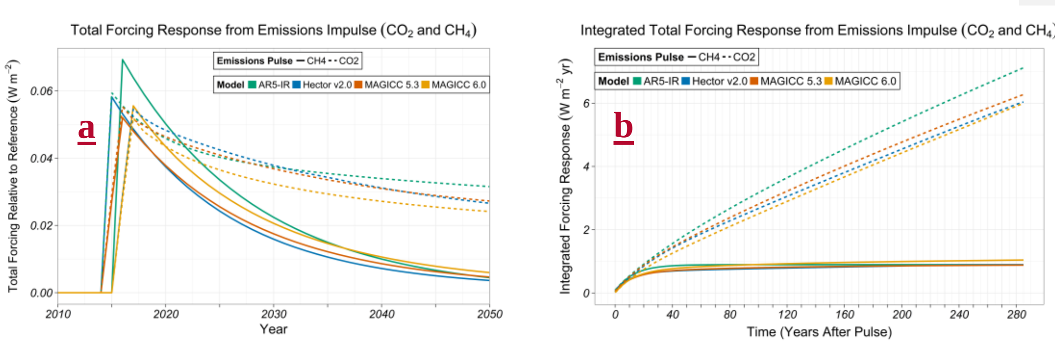
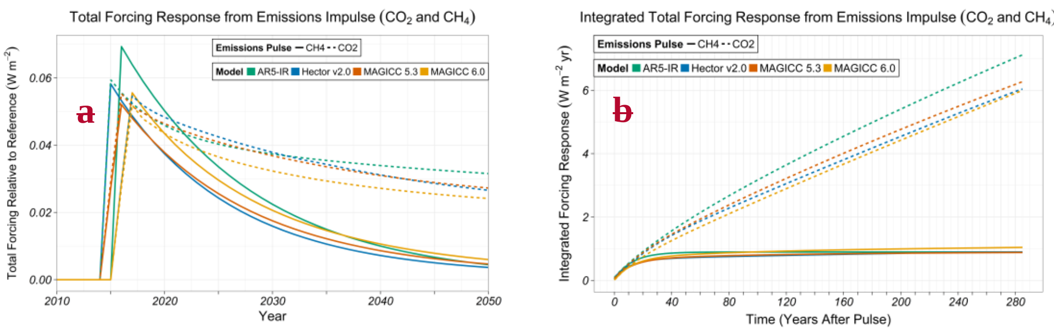


Figure 2: Total forcing response from CO_2 (dashed) and CH_4 (solid) emissions perturbations in SCMs (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, AR5-IR – green). FAIR does not report forcing. We report the total forcing response, which has slight differences from the gas-only forcing response. The perturbations are conducted in 2015 against the background of the Representative Concentration Pathway (RCP) 4.5 scenario (see Methods). The time-integrated response, analogous to the Absolute Global Warming Potential, is reported as 0-285 years after the perturbation.

We complete the model response sequence by examining the temperature response from emissions perturbations, which is conceptually the combination of the temperature response from a concentration impulse (Fig. 1) and the forcing response from an emissions impulse (Fig. 2). Similarities in the comprehensive SCM responses in Figs. 1 and 2 are reflected in the <5% difference in the temperature response from a CO_2 emissions perturbation 20 years after the impulse (Fig. 3a~~3b~~). AR5-IR responds 30% stronger and FAIR <10% weaker compared to the comprehensive SCM~~SCMs~~ average 20 years after the perturbation (Fig. 3a). FAIR introduces a state-dependent carbon cycle representation (Millar et al., 2017) and is, in general, an improvement over AR5-IR, but shows a systematic difference with the comprehensive SCMs.



~~**Figure 2: Total forcing response from CO_2 (dashed) and CH_4 (solid) emissions perturbations in SCMs (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, AR5-IR – green). FAIR does not report forcing. We report the total forcing response, which has slight differences from the gas-only forcing response. The perturbations are conducted in 2015 against the background of the Representative Concentration Pathway (RCP) 4.5 scenario (see Methods). The time-integrated response, analogous to the Absolute Global Warming Potential, is reported as 0-285 years after the perturbation.**~~

We indirectly compare the time-integrated airborne fraction in our SCMs to three comprehensive ESMs and seven Earth System Models of Intermediate Complexity (EMICs) using results from the Joos et al. (2013) 100 GtC CO_2 pulse experiment, henceforth referred to as Joos et al.~~.~~ Unlike Joos et al., we conduct this experiment with a changing background concentration (S12~~SI11~~). The airborne fraction is, therefore, higher in our results. Despite the difference in methodology, comparing the MAGICC 6.0 results here and in Joos et al. allows us to use transitive logic to draw broader conclusions about the other comprehensive SCMs. We note that the Joos et al. MAGICC 6.0 ensemble mean airborne fraction is similar to their multi-model mean at each time horizon (Fig. S28~~S23~~). Because Hector and MAGICC 5.3 have a similar response to MAGICC 6.0 in our results, we conclude that the comprehensive SCM carbon cycle representations generally capture ESM and EMIC responses to the extent this can be evaluated for indirect comparison.

Similarly, we compare the temperature response of the comprehensive SCMs to Joos et al. We find that the comprehensive SCMs capture ESM and EMIC responses in the near-term, with expected differences in response over longer time horizons due to rising background concentrations (S12~~SI11~~).

For idealized SCMs, we find that under changing background conditions, FAIR underestimates the airborne fraction compared to the Joos et al. multi-model mean at each time horizon. Without a physical processes-based carbon cycle, AR5-IR is insensitive to pulse size and background concentration (Millar et al., 2017), which results in a similar time-integrated airborne fraction compared to the Joos et al. multi-model mean at each time horizon. The comprehensive SCMs and to a lesser extent, FAIR, offer an improved response compared to AR5-IR (Millar et al., 2017).

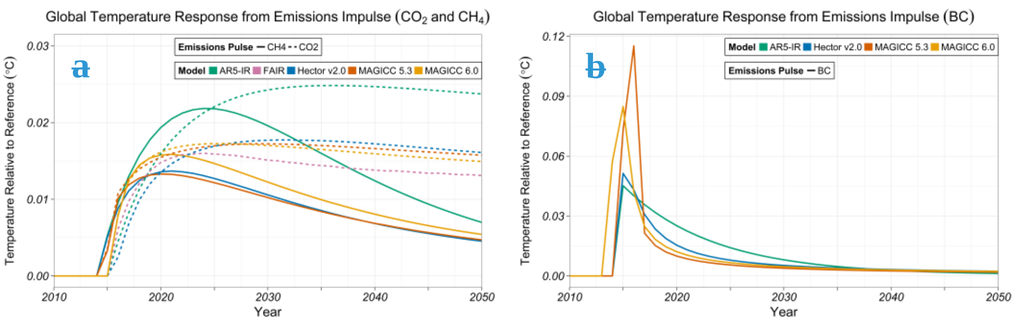


Figure 3: Global mean temperature response from CO_2 and CH_4 emissions perturbations (a) and BC emissions perturbation (b) in SCMs (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, AR5-IR – green, FAIR – pink).

We next consider model responses to methane (CH_4) emissions perturbations, a shorter--lived greenhouse gas with a dynamic atmospheric lifetime (see S1SI1). The integrated forcing responses of Hector and MAGICC 5.3 are similar, as expected (S9.3SI17). The MAGICC 6.0 integrated forcing response from MAGICC 6.0, however, shows a larger difference from the comprehensive SCM average is (9% larger%) 100 years after the pulse, however (Fig. 2b). As in the CO_2 emissions perturbations, AR5-IR has a much stronger response (22%) to a CH_4 emissions perturbation—22% larger 20 years after the pulse—, with no meaningful increase 50 years after the pulse (S9SI8).

Finally, we look at the models' temperature responses to aerosols by perturbing black carbon (BC) forcing (Fig. 3b 3). The BC response increases quickly in both MAGICC models compared to the other SCMs (S9.4SI9). Differences in these responses to a BC perturbation derive from model design. Both versions of MAGICC have differential and faster forcing responses over land, where most BC is located, compared to oceans, termed the geometrical effect (Meinshausen et al., 2011). This results in MAGICC responding faster than Hector v2.0, which does not differentiate forcing over land and ocean. Because AR5-IR represents the aerosol forcing as an exponential decay, the integrated temperature response is 20% stronger 20 years after the pulse compared to the other SCMs.

Due to the geometrical effect, we presume that the faster response in MAGICC is more realistic. However, models vary in the representations of aerosol effects (S2SI2). The greenhouse gas-like representation of aerosols in AR5-IR, for example, results in the unrealistically long response time scale found in this test. We do not explicitly conduct other aerosol perturbations (e.g., sulfate), but we would expect results showing similar responses.

BC has a unique set of atmospheric interactions, acting as an absorbing aerosol, and causing inhomogeneous warming within the atmosphere, but potentially also surface cooling (Stjern et al., 2017). The response to a step change in BC emissions in two coupled model experimentsin BC has been found to have a flat long-term temperature response (Sand et al., 2016). In contrast, the We find that comprehensive simple models continue to respond over a much longer time scale (S13).than an ESM experiment investigating the climate response to BC (SI12). This is an indication that SCM responses to BC, in particular, should be reevaluated.

3.3 Responses to 4xCO_2 Concentration Step. Finally, we compare our SCMs with complex models using the abrupt 4xCO_2 concentration experiment from Phase 5 of the Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2012) (see S1SI1 and S3SI3). We find that Hector, MAGICC 5.3, and FAIR have initially quicker responses to an abrupt 4xCO_2 concentration increase (Fig. 4). This is also reflected in their long term RWF, which is also larger than most of the complex models (see S10SI9). Compared to the other SCMs, AR5-IR has a fasterslower response to an abrupt 4xCO_2 concentration increase and is consistent withwhich does not substantially increase 25 years after the stronger response to pulse, reflected in a forcing impulse.lower RWF. Differences between the model responses to a finite pulse (Fig. 1) and a large concentration step (Fig. 4) demonstrates the expected bias in AR5-IR under larger perturbations. The insensitivity of idealized SCMs to changing background concentrations will bias results if used under realistic future pathways (Millar et al., 2017).

Compared to the other comprehensive SCMs, MAGICC 6.0 initially responds more strongly under a CO_2 concentration impulse (Fig. 1). In the non-linear abrupt 4xCO_2 concentration regime, however, MAGICC 6.0 responds more slowly, similar to the complex model responses, especially in the first 20 years after the pulse. MAGICC 6.0 appears to respond more reasonably under stronger forcing conditions than the other SCMs.

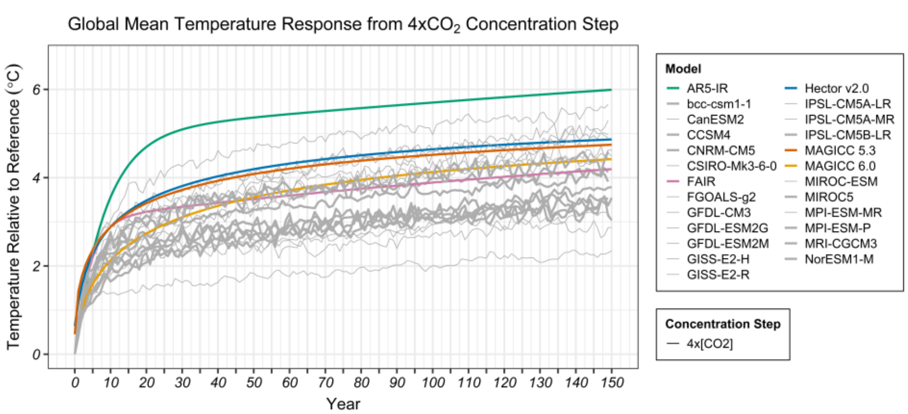


Figure 4: Global mean temperature response from 4xCO_2 concentration step in CMIP5 models (grey) and SCMs (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, FAIR – pink, AR5-IR –green). A climate sensitivity value of 3°C was used in the SCMs and the thick lines represent CMIP5 models with an ECS between 2.5 - 3.5 °C.

Figure 4: Global mean temperature response from 4xCO2 concentration step in CMIP5 models (grey) and SCMs (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, FAIR – pink, AR5-IR –green). A climate sensitivity value of 3°C was used in the SCMs and the thick lines represent CMIP5 models with an ECS between 2.5 - 3.5 °C.

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4 Conclusions

The impulse response tests conducted here enable us to uncover differences in model behavior that are not apparent when running standard, multi-emission scenarios. Indeed, one of the important uses of SCMs is to conduct model experiments where there may be relatively small changes in emissions between two scenarios. Because SCMs do not exhibit internal variability, such experiments can be used to quantify such changes. Impulse response tests also allow us to understand, on a more fundamental level, differences between SCMs that have been found comparing simulations of more conventional scenarios (e.g., van Vuuren et al., 2011).

By using fundamental impulseunit tests, we found that idealized SCMs using sums of exponentials often fail to capture the responses of more complex models. SCMs that include representations of non-linear processes, such as FAIR, show improved responses, though these models still do not perform as well as comprehensive SCMs with physically-based representations. Fundamental forcing tests, such as a 4xCO_2 concentration step, show that most of thesome SCMs used here(Hector, MAGICC 5.3, and FAIR) have a faster warming rate in this strong forcing regime compared to more complex models. However, comprehensive SCM responses are similar to more complex models under smaller, more realistic perturbations (Joos et al., 2013).

It is not possible to compare these fundamental responses with observations, and it is even more difficult to compare SCMs with the more complex models at decadal time horizons due to internal variability (e.g., Joos et al., 2013, Figure 2a). However, it is common in the climate modeling literature to use the multi-model mean as a base comparison. In fact, the CMIP5 multi-model mean has been shown to replicate observations better than any individual complex model (Flato et al. 2013).

Thus, we use the comprehensive SCM multi-model mean to compare to the individual model responses for most of our experiments. We also use the CMIP5 multi-model mean, developed using only those complex models with comparable climate sensitivity values to the SCMs (S10), to compare the SCM responses from a 4xCO_2 forcing step. We posit that the responses closer to the multi-model mean are likely to more accurately represent that particular response pattern. We illustrate this assumption by reporting the time-integrated temperature response percent difference from the relevant multi-model mean in Table 1 (S14). Additional time-integrated temperature responses can be found in S9.

We note that the comprehensive SCM responses to a CO_2 concentration impulse are within 2% of the comprehensive SCM average, while the idealized SCMs, FAIR v1.0 and AR5-IR, have greater differences 100 years after the pulse.

Under the 4xCO_2 concentration step experiment, we can compare the SCM responses to more complex models from CMIP5. MAGICC 6.0 appears to respond more reasonably under stronger forcing conditions than the other SCMs 100 years after the pulse, though only marginally better than FAIR. Hector v2.0, MAGICC 5.3, and FAIR have initially quicker responses to an abrupt 4xCO_2 concentration increase compared to the ESMs. AR5-IR has too strong a response to an abrupt 4xCO_2 concentration increase and is insensitive to changing background concentrations.

For CH_4 emissions impulses, we use the difference from the comprehensive SCM average to rate the responses. CH_4 is a well-mixed GHG and, therefore, we expect that the climate system response to CH_4 concentration perturbations will be similar to that for CO_2. However, it would be useful to evaluate in more complex models to determine if the simple representation of chemistry in the comprehensive SCMs adequately represents the time evolution of CH_4 concentrations in response to a change in emissions.

Finally, we do not have a definitive reference for the time-dependent response to BC forcing perturbations. Instead, we compare the SCMs using the difference from the average of both MAGICC models, which both differentiate aerosol forcing between land and ocean, resulting in a faster overall climate response to aerosols as compared to greenhouse gases (Shindell et al., 2014; Sand et al., 2016; Yang et al. 2019). And in the case of BC, we note that the SCM responses should be taken critically because they do not accurately represent the temporal response to a BC step found in ESMs. A more definitive evaluation of climate system responses to aerosol perturbations would be useful. This would require additional complex model simulations of step emission changes for various aerosol species and/or forcing mechanisms. There are currently two studies that have conducted this test, one study specifically investigated NorESM's response to black carbon (BC) perturbations (Sand et al., 2016) and a more recent study that conducted similar BC perturbations in CESM (Yang et al., 2019).

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			Percent Integrated Temperature Response Differences for each Simple Climate Model (%)Model					
Species	**Impulse**	**Time After PulseSpecies**	**Hector v2.0**	**MAGICC 5.3**	**MAGICC 6.0**	**FAIR v1.0**	**AR5-IR**	
CO_2	4x Forcing Step	H = 100 yrsCO_2 impulse	38%•••	35%•••	15%•••	18%••	73%•	
	Forcing Impulse4xCO_2 step	H = 100 yrs••	1.0%••	-1.2%•••	0.25%••	-16%•	23%-	
	GHG Emissions	H = 100 yrsCO_2	-0.57% •••	2.2%•••	-1.6% •••	-14% ••	31% •	
	CH_4	GHG Emissions•••	H= 20 yrs•••	-3.1% •••	-5.6% —	8.7% ••	--	47%
Aerosols*	SO_2, BC	Aerosol Emissions••	H = 20 yrs•••	-9.3%•••	1.1%—	8.1%•	--	19%

There are numerous benefits to using simplified models, but the selection of the model should be rooted in a clear understanding of the model responses (see Table 1). Our work illustrates the necessity of using fundamental impulseunit tests to evaluate SCMs and we recommend that modeling communities adopt them as a standard validation suite for any SCM.. Given that idealized SCMs are biased in their temporal responsesresponse patterns, more comprehensive SCMs could be used for many applications without compromising on accessibility or computational requirements.

Table 1: Percent Integrated Temperature Response Differences.Summary of SCM Performance. The values areperformance scale is generally based on the percentmaximum difference in time-integrated temperature response compared to the relevant reference (generally comprehensive SCM average in S9). *SI 9). ••• : 0-10%, •• : 10-20%, • : 20-30% difference (SI13). * This ranking refers to aerosol response in general, which do not differ substantially for different aerosol types in these models. For BC specifically, we note thatall ratings should be reduced since none of the SCMs reflectaccurately represent the temporal response for BC seen in two ESMs (Sand et al., 2016) **(S14SI12).**

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Author contribution. SJS, CAH, and AKS contributed to experiment design and figure development. AKS performed the experimental simulations and developed the AR5-IR model code in R. AKS prepared the manuscript with contributions from all co-authors.

Conflict of Interest. The authors declare that they have no conflicts of interest.

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~~The views and opinions expressed in this paper are those of the authors alone.~~

Code Availability

All model input files generated for our experiments, and the resulting impulse response functions, are provided in the Supplementary Materials or online at https://github.com/akschw04/Fundamental-Impulse-Tests-in-SCMs-Datasets.. The authors appreciate that any use of this data be attributed.

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Supplement: Evaluating Climate Emulation: Fundamental Impulse~~Unit~~ Testing of Simple Climate Models

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Contents

S1 Supplementary Method

We conduct perturbations of three contrasting chemical species: carbon dioxide (CO_2), methane (CH_4), and black carbon (BC). We begin with CO_2 because this well-mixed greenhouse gas is the largest contributor to anthropogenic forcing changes (Myhre et al., 2013). Methane is also of interest because it is a shorter-lived greenhouse gas, with chemical interactions with itself and other species (Cicerone, R.J.; Oremland, 1988). Finally, we use BC perturbations to represent aerosols more generally because we are interested in model responses to short-lived climate forcers (Bond et al., 2013; Harmsen et al., 2015). SCM representations of other aerosols species are similar so we do not conduct impulse tests of other species.

The comprehensive SCMs we use are readily comparable because they read in similar emissions. Background trajectory emissions are taken from the published Representative Concentration Pathway (RCP) 4.5 scenario (Thomson et al., 2011) database, which means that all calculations in the main paper are conducted relative to a changing CO_2 concentration background unless otherwise noted. SCMs are often used to project global mean temperature over various future scenarios, so this is the most relevant type of background on which to test these models.

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Conducting these experiment with a constant CO_2 background, as previously used in the literature (Joos et al., 2013), requires inverse modeling of the individual models to produce constant CO_2 concentration emissions files. Our methodology is easier to implement as a regular unit test as it only requires the same emissions inputs with no inverse calculations needed. We provide the input emission files used in this paper.

In many SCMs, forcing over historical periods is explicitly calibrated to a model base year, so it is not possible to conduct perturbations during these time periods. Therefore, our perturbations are conducted in 2015 to avoid the model base years of our SCMs. In the main paper, we show some model responses out to 2300, the end of the MAGICC model runs, equal to 285 years after the perturbation. Additional results are in S8.We note that unit testing in software refer to a specific method of comparing output from the smallest portion of code, called a unit (i.e., function), to known outputs (Clune and Rood 2011). Here, we use this term in a similar way as van Vuuren *et al.* (van Vuuren et al. 2011), where MAGICC 6.0 was used as the reference output to compare several human-Earth system models. We conduct our unit test with comparable inputs and compare model-generated outputs from several SCMs.

We conduct perturbations of three contrasting chemical species: carbon dioxide (CO_2), methane (CH_4), and black carbon (BC). We begin with CO_2 because this well-mixed greenhouse gas is the largest contributor to anthropogenic forcing changes (Myhre et al. 2013). Methane is also of interest because it is a shorter-lived greenhouse gas, with chemical interactions with itself and other species (Cicerone, R.J.; Oremland 1988). Finally, we use BC perturbations to represent aerosols more generally because we are interested in model responses to a short-lived climate forcers (Bond et al. 2013; Harmsen et al. 2015). SCM representations of other aerosols species are similar so we do not conduct impulse tests of other species.

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We run reference scenarios in the SCMs, followed by each perturbation case described below. For each experiment (see below) we report the response, which is obtained by subtracting the reference from the perturbation results. For instance, the CO_2 concentration response is obtained as follows:

$$CO_2Concentration_{response}(t) = CO_2Concentration_{perturabtion}(t) - CO_2Concentration_{reference}(t) \quad (1)$$

We conducted the following impulse tests:

a. Concentration impulse (CO_2).

These SCMs can be used in a mode where CO_2 concentrations are exogenously specified. We carry out this experiment by instantaneously increasing CO_2 concentration by 200 ppm in 2015. After 2015, CO_2 concentrations return to the baseline levels following the published RCP4.5 scenario. Note, we do not conduct separate forcing impulse experiments because this is functionally equivalent to a concentration impulse. In this experiment, we are only interested in the dynamics of the models' temperature response. This experiment eliminates the added uncertainty in the emissions to concentrations calculation and complicating factors from carbon cycle feedbacks.

b. Emissions impulse (BC, CH_4, CO_2).

For this experiment all models were run with an emissions input. We carry out this experiment by increasing individual emissions (BC, CH_4, or CO_2) in one year. Following that year, the emissions return to the RCP4.5 pathway for all subsequent years. In this experiment CO_2 and other GHG concentrations are allowed to vary as determined by each model. We find our perturbation values by doubling the 2015 value for each chemical species equal to a 9.2 PgC pulse of CO_2, a 329 Tg pulse of CH_4, and a 7981 Gg pulse of BC. We also perturb CO_2 emissions in 2010, 2020, 2030, 2040, 2050 to understand changes in model responses over time and see a very small difference in the model response (S4). We compare results from three comprehensive SCMs to two IR models, AR5-IR and FAIR model (Millar et al., 2017; Myhre et al., 2013) (S2~~In this experiment CO_2 concentrations are allowed to vary as determined by each model. We find our perturbation values by doubling the 2015 value for each chemical species equal to a 9.2 PgC pulse of CO_2, a 329 Tg pulse of CH_4, and a 7981 Gg pulse of BC. We also perturb CO_2 emissions in 2010, 2020, 2030, 2040, 2050 to understand changes in model responses over time and see very small difference in the model response (SI5). We compare results from three comprehensive SCMs to two IR models, AR5-IR and FAIR model (Millar et al. 2017; Myhre et al. 2013) (SI2~~).

We also compared results to several ESMs and EMICs by carrying out a 100 GtC CO_2 impulse, following Joos et al. (Joos et al., 2013) (S12). This is approximately 10x the CO_2 perturbation pulse described above.

Finally, we conduct a 4xBC emissions step experiment. We compare the SCM temperature responses with the response of a complex climate model used by Sand et al. (2016) (S13).

~~We also compared results to several ESMs and EMICs by carrying out a 100 GtC CO_2 impulse, following Joos *et al*. (Joos et al. 2013) (SI11). This is approximately 10x the CO_2 perturbation pulse described above.~~

Finally, we conduct a 4xBC emissions step experiment. We compare the SCM temperature responses with the response of a complex climate model used by Sand *et al.* (Sand et al. 2016) (SI12).

c. Step increase in CO_2 concentration (instantaneous 4×CO_2 concentration experiment). Similar to comparison (a), in this experiment, CO_2 concentrations are prescribed. We have CO_2 concentrations follow a pre-industrial pathway (278.0516 ppmv in 1765) until 2014. The CO_2 concentration is quadrupled (4x) in 2015, and maintained at this level until 2300. This follows the experimental protocol used in the CMIP5 experimental design (Taylor et al., 2012)(Taylor, Stouffer, and Meehl 2012).

We compare these results to drift-corrected (Gupta et al., 2013) global mean temperature results from 20We compare these results to drift-corrected (Gupta et al. 2013) global mean temperature results from 15 complex climate models from the CMIP5 archive. We drift-correct the CMIP5 global mean temperature time series by subtracting the slope of the linear fit from the full- -time series of the corresponding pre-industrial experiment for each individual model (see S3)..

We ran Hector v2.0 with few changes to the default configuration file settings. We changed two model time steps in Hector v2.0: (1) the carbon-cycle-solver.cpp time step from dt(0.3) to dt(0.1) and (2) the ocean_component.hpp OCEAN_MIN_TIMESTEP from 0.3 to 0.01 to allow for the carbon cycle, in particular, the ocean carbon cycle to accurately integrate across the sharp gradient introduced by these experiments. In experiments where we constrained the CO_2 concentration, these changes significantly increase the model run time for this scenario.

Additionally, we used an equilibrium climate sensitivity (ECS) value of 3°C in the SCMs, with the exception of the idealized SCMs, FAIR and AR5-IR (see Table S9). In both FAIR and AR5-IR ECS is an emergent property from the choice of ocean parameters given by,, where these parameters cannot be set by the user (see Table S9).

$$ECS = F_{2x}(q_1 + q_2) \qquad (2)$$

where F_{2x} is the forcing due to CO_2 doubling ($F_{2x} = 3.74\ Wm^{-2}$) and both q_1 and q_2 are the ocean parameters thermal adjustment of the upper ocean and thermal equilibrium of the deep ocean, respectively (Millar et al. 2017; Equation 4).

We conducted additional sensitivity experiments in the SCMs spanning ranges of climate sensitivity and ocean diffusivity and report the results in S11.

S2 Discussion of Model Specifications~~Design~~

We conduct unit tests within three comprehensive SCMs and two stylized SCMs. The three comprehensive SCMs have structural differences worth noting. Hector v2.0, has explicit ocean carbon chemistry in four boxes, where ocean carbon uptake is a non-linear function of the solubility of carbon. MAGICC 5.3 BC-OC and 6.0 have differential hemispheric forcing over land and ocean, thereby calculating temperature over each box. Important characteristics of the carbon and climate components of each model are shown in Table S1.

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Table S1 Main carbon cycle and climate characteristics of SCMs and IRFs

Model	Model description	Carbon cycle	Climate component
Hector v2.0 (Hartin et al., 2015, 2016; Kriegler, 2005)~~Hector v2.0 (C. A. Hartin et al. 2015; Corinne A Hartin et al. 2016; Kriegler 2005a)~~	mechanistic climate carbon-cycle model	One-pool atmosphere, three-pool land, and four-pool ocean	Global Energy balance model, with ocean heat diffusion
MAGICC 5.3 BC-OC (Raper and Cubasch, 1996; Smith and Bond, 2014; Wigley and Raper, 1992)~~MAGICC 5.3 BC-OC (Raper and Cubasch 1996; S. J. Smith and Bond 2014; Wigley and Raper 1992)~~	mechanistic climate carbon-cycle model	One-pool atmosphere, three-pool land, and one-pool ocean	4-box Energy balance model, with ocean heat upwelling diffusion
MAGICC 6.0 (Meinshausen et al., 2011)~~MAGICC 6.0 (Meinshausen, Raper, and Wigley 2011)~~	mechanistic climate~~-~~carbon cycle model	One-pool atmosphere, three-pool land, and one-pool ocean	4-box Energy~~boxEnergy~~ balance model, with ocean heat upwelling diffusion
AR5-IR (Myhre et al., 2013)~~AR5-IR (Myhre et al. 2013)~~	Impulse-response function	Impulse-response function	Equilibrium temperature as a function of RF
FAIR v1.0 (Millar et al., 2017)~~FAIR v1.0 (Millar et al. 2017)~~	Impulse-response function	Four timescale impulse-response function with state-	Equilibrium temperature as a function of RF; IRF with two timescales

		dependence of the CO_2 airborne fraction	

Some SCMs also include representations of aerosol dynamics, though the model representations differ. As mentioned in the main paper, unlike Hector v2.0, both versionsversion of MAGICC have differential hemispheric forcing over land and ocean. AR5-IR represents BC forcing response as a simple exponential, similar to the response from greenhouse gas forcing. FAIR v1.0, used here, represents the relationship between CO_2-only emissions, concentrations, and temperature. Other versions of FAIR include non-CO_2 forcing, such as BC.

S2.1 Model Settings

Here we discuss the model settings used in our experiments, noting any changes made to the default settings. The three comprehensive SCMs were run with the same ECS values unless otherwise noted. We also acknowledge that vertical ocean diffusivity has a large impact on ocean heat uptake and we do note that the SCMs we compare in our paper either do not have the same definitions of vertical ocean diffusivity, as is the case for the comprehensive SCMs, or ocean diffusivity is not directly represented in the models, as is the case for idealized SCMs. For our purposes, therefore, we kept the ocean diffusivity values at their default values within the comprehensive SCMs. Sensitivity experiments exploring the model response to the range of these two parameters derived from MAGICC 6.0 are available in S11The three comprehensive SCMs were run with the same ocean diffusivity value and ECS value, unless otherwise noted.

S2.2 AR5-IR

The IPCC AR5 (Myhre et al. 2013; See caption under Figure 8.28) describes the underlying multi-gas impulse response model used to quantify the multi-gas equivalence metric, Absolute Global Temperature Potential (AGTP), to compare temperature changes at a chosen time in response to a unit pulse of emissions *i*. We refer to this model as AR5-IR and describe below how the sums of exponentials are used to find AGTP and the subsequent temperature response. AGTP is found via a convolution of the fraction of the species *i* remaining in the atmosphere after an emissions pulse and the climate response to a unit forcing,

$$R_T(t) = \sum_{j=1}^{M} \frac{c_j}{d_j} \exp\left(-\frac{t}{d_j}\right) \quad (3;\ \text{See Equation 8.SM.13}).$$

~~The IPCC AR5 (Myhre et al. 2013) describes a multi-gas impulse function using a multi-gas equivalence metric, Absolute Global Temperature Potential (AGTP), to compare temperature changes at a chosen time in response to a unit pulse of emissions *i*. AGTP is found via a convolution of the fraction of the species *i* remaining in the atmosphere after an emissions pulse and the climate response to a unit forcing $R_T(t) = \sum_{j=1}^{M} \frac{c_j}{d_j} \exp(-\frac{t}{d_j})$ (1).~~

$$AGTP_i(H) = \int_0^H RF_i(t) R_T(H-t)\,dt$$ (4; See 8.SM.14 ~~(2~~)

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and $RF_i(t) = A_i R_i(t)$ (5; See Equation 8.SM.7~~,~~ ~~(3~~)

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where for most species $R_i(t) = \exp(-\frac{t}{\tau_i})$ (6; See Equation 8.SM.8)~~,~~ ~~(4~~)

and for CO_2 $R_{CO_2}(t) = a_0 + \sum_{i=1}^{N} a_i \exp(-\frac{t}{\tau_i})$ (7; See Equation 8.SM.10)~~,~~ ~~(5~~)

and A_i is the radiative efficiency yielding, the general equation:

$$AGTP_i(H) = A_i \sum_{j=1}^{2} \frac{\tau c_j}{\tau - d_j}\left(\exp\left(\frac{-H}{\tau}\right) - \exp\left(\frac{-H}{d_j}\right)\right)$$ (8; See Equation 8.SM.14 ~~(6~~)

AGTP can then be used to calculate global mean temperature change from any given emission scenario using,

$$\Delta T = \sum \int_o^t E_i(s) AGTP_i(t-s)\,ds$$ (9; See Equation 8.1 ~~(7~~)

where E_i are the emissions of a species, t is the time horizon, and s is the time of emissions (Myhre et al. 2013; See 8.7.13 and Equation 8.1). For this paper, AR5-IR was recoded in R and is available for download with the Supplementaty Materials.

S2.3 FAIR

The FAIR v1.0 model is a modified version of the AR5-IR carbon cycle component to include the state-dependence of the CO_2 airborne fraction to reproduce the relationship between CO_2-only emissions, concentrations, and temperature over the historical period. Millar et al. (2017) began with the impulse response functions used for calculation of multi-gas equivalence metrics in IPCC-AR5 (Myhre et al., 2013) and extended the CO_2 IRF by coupling the carbon-cycle to the thermal response and to cumulative carbon uptake by terrestrial and marine sinks. FAIR is available for download at where E_i are the emissions of a species, t is the time horizon, and s is the time of emissions(Myhre et al. 2013). For this paper, AR5-IR was recoded in R and is available for download with the Supplementaty Materials.

S2.3 FAIR

The FAIR v1.0 model is a modified version of the AR5-IR carbon cycle component, updated to include the state-dependence of the CO_2 airborne fraction to reproduce the relationship between CO_2-only emissions, concentrations, and temperature over the historical period. Millar *et al.*(Millar et al. 2017) began with the impulse response functions used for calculation of multi-gas equivalence metrics in IPCC-AR5(Myhre et al. 2013) and extended the CO_2 IRF by coupling the carbon-cycle to the thermal response and to cumulative carbon uptake by terrestrial and marine sinks. FAIR is available for download at https://github.com/OMS-NetZero/FAIR.

FAIR calculates the global mean temperature response as the sum of the temperature response from the fast and slow timescale components, which represent the upper and deep ocean. The model does not report the internally-calculated forcing response, so this is not included in Figure 2 in the main paper.

Here, we use the first iteration of FAIR, but we note that two new versions have recently been published, FAIR v1.1 and FAIR v1.3. FAIR v1.3 extends the original version to, "calculate non-CO_2 greenhouse gas concentrations from emissions, aerosol forcing from aerosol precursor emissions, tropospheric and stratospheric ozone forcing from the emissions of precursors, and forcings from black carbon on snow, stratospheric methane oxidation to water vapour, contrails and land use change (Smith et al., 2018)."

S2.4 FAIR (without carbon cycle) versus AR5-IR

We expect slight differences in the response of FAIR and AR5-IR to a unit forcing. According to Equation 8 in Millar et al. (2017), FAIR will have a differential response to changing background CO_2 concentrations. By contrast, AR5-IR parameterizes the climate response to a unit forcing, R_T, using a sum of exponentials as given by Equation 8.SM.13 in Myhre et al. (2013):

$$R_T(t) = \sum_j \frac{q_j}{d_j} e^{\frac{-t}{d_j}} \quad \text{(10; See Equation 8.SM.13)}$$

Values of the R_T input parameters, q_j and d_j, are available in Table S2 of this response, where j=1,2 represent the timescales of the fast and slow ocean response. We note all parameters are independent of background concentration in AR5.

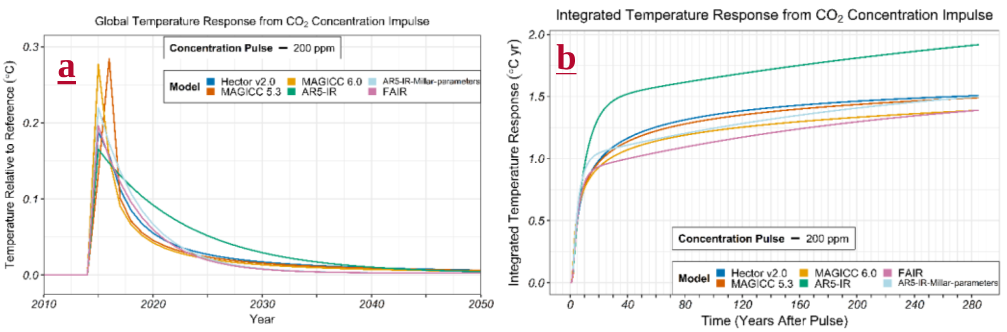
In the main paper, we used the time constant parameters representing the thermal equilibrium of the deep ocean (d2) and the thermal adjustment of the upper ocean (d1) from Myhre et al. (2013), rather than from Millar et al. (2017). We are testing the model responses as they would be 'out of the box' and only make modifications if required for the models to run, as was the case for Hector v1.1 to handle a 4xCO_2 concentration step.

Here we included additional model responses from the AR5-IR model using parameters from Millar et al. (2017). The parameter choices are available below in Table S2.

Table S2 Parameter values for the simple impulse-response model, AR5-IR

Parameter (Units)	Value – AR5-IR (from Myhre et al., 2013)	Value – AR5-IR-var (from Millar et al., 2017)	Guiding analogues
α (Wm^{-2})	5.35	5.395 (α = F2x/ln(2); F2x=3.74)	CO_2 RF scaling parameter
q_1 ($KW^{-1}m^2$)	0.631	0.41	Thermal adjustment of the upper ocean
q_2 ($KW^{-1}m^2$)	0.429	0.33	Thermal equilibrium of the deep ocean
d_1 (year)	8.4	4.1	Thermal adjustment timescale of the upper ocean
d_2 (year)	409.5	239.0	Thermal equilibrium timescale of the deep ocean

Figure S1 shows the temperature response from a CO_2 concentration impulse and Figure S2 shows the temperature response from a CO_2 concentration step in several SCMs, including the AR5-IR response found using the Millar et al. (2017) time constants, which we refer to as "AR5-IR-Millar-parameters" in this figure. We note that the AR5-IR-parameters response is still not identical to FAIR because FAIR has a differential response to changing background CO_2 concentrations.



concentration perturbation in SCMs (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, AR5-IR – green, FAIR –pink, AR5-IR-Millar-parameters –light blue). The time-integrated response, analogous to the Absolute Global Temperature Potential, is reported as 0-285 years after the perturbation.

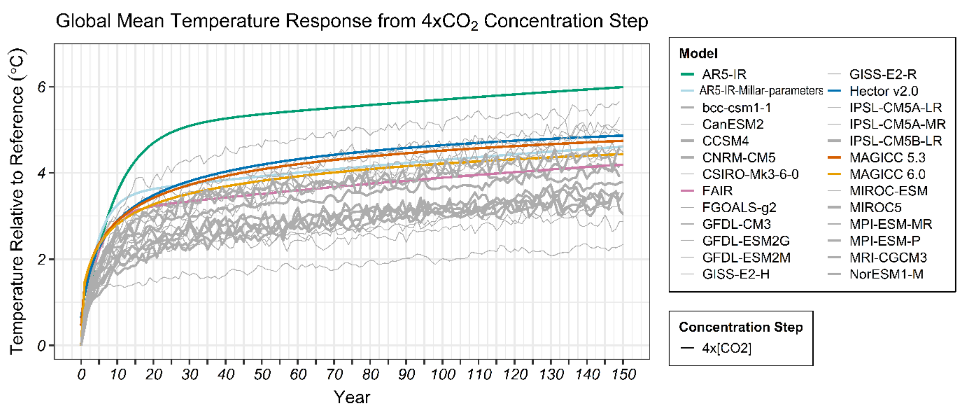


Figure S2 *Global mean temperature response from 4xCO_2 concentration step in CMIP5 models (grey) and SCMs (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, FAIR – pink, AR5-IR – green, AR5-IR-Millar-parameters – light blue). A climate sensitivity value of 3°C was used in the SCMs and the thick lines represent CMIP5 models with an ECS between 2.5 - 3.5 °C.*

We note that, while the Millar et al. (2017) parameters in Table S2 may provide a better short-term fit, they underestimate the long-term response of the ocean. The long-term ocean thermal time scale, which can only be estimated using multi-century model runs, is known to be longer than 200 years from basic physical principles (as seen in the original literature cited by the AR5 model, which used longer model runs to inform those parameters). While this may be an acceptable tradeoff if this model is only going to be used over a 100-year timescale, this will inevitably lead to bias on longer time-scales. The simple climate models tested in this study are used for a variety of purposes and over a range of time-scales. This illustrates why we use the original parameters of the models as set by their designers.

~~Here, we use the first iteration of FAIR, but we note that two new versions have recently been published, FAIR v1.1 and FAIR v1.3. FAIR v1.3 extends the original version to, "calculate non-CO_2 greenhouse gas concentrations from emissions, aerosol forcing from aerosol precursor emissions, tropospheric and stratospheric ozone forcing from the emissions of precursors, and forcings from black carbon on snow, stratospheric methane oxidation to water vapour, contrails and land use change (C. J. Smith et al. n.d.)."~~

S2.4 MAGICC 5.3 BC-OC

MAGICC 5.3 BC-OC is a version of MAGICC 5.3 developed in conjunction with the Global Change Assessment Model (GCAM). MAGICC 5.3 used here is available in GCAM version 4.4, available for download at https://github.com/JGCRI/gcam-core/releases. The major change in this version of MAGICC was the addition of explicit BC and OC (Smith and Bond, 2014).(S. J. Smith and Bond 2014). To enable MAGICC 5.3 within GCAM, the climate model must be set to <Value name = "climate">../input/climate/magicc.xml</Value> within the configuration file. We ran this model with all its default configuration settings, unless otherwise noted in the text.

S2.5 MAGICC 6.0

MAGICC 6.0 was run with all the default settings. For the main experiments, the climate sensitivity was set to 3.0°C to match the default setting of MAGICC 5.3 BC-OC and Hector v2.0, unless otherwise noted. The MAGICC 6.0 executable is available for free download here: http://www.magicc.org/.

S2.6 Hector v2.0 Settings

In the version we use here, Hector (v2.0), is coupled to a 1-D diffusive heat and energy balance model (DOECLIM: Diffusion Ocean Energy balance CLIMate model). We are using the 1-D diffusive ocean heat component of DOECLIM. DOECLIM is well documented and has been widely used in climate uncertainty studies (Bakker et al., 2017; Kriegler, 2005; Urban et al., 2014). Using default Hector parameter values for climate sensitivity and heat diffusivity, we find that the new coupled model (Hector v2.0) exhibits improved vertical ocean structure and heat uptake, as well as surface temperature response to radiative forcing, compared to earlier versions of Hector.

S3 CMIP5 Model Data

~~We use a new version of Hector (v2.0), an open-source, object-oriented, simple global climate carbon-cycle model (C. A. Hartin et al. 2015). The model can found at: http://github.com/JGCRI/hector. In the version used here (Hector v2.0), Hector v1.0 is coupled to a 1-D diffusive heat and energy balance model (DOECLIM: Diffusion Ocean Energy balance CLIMate model). DOECLIM is well documented and has been widely used in climate uncertainty studies (Bakker et al. 2017; Kriegler 2005b; Urban et al. 2014). DOECLIM includes three tunable parameters: climate sensitivity, ocean vertical heat diffusivity, and a scaling factor for aerosol forcing (Garner, Reed, and Keller 2016). Using default values for these parameters, we find that the new coupled model (Hector v2.0) exhibits improved vertical ocean structure and heat uptake, as well as surface temperature response to radiative forcing, compared to earlier versions of Hector.~~

~~S3 CMIP5 Model Data~~

The CMIP5 model data used to produce Figure 4~~, Figure S12, and Figure S22~~ is described here. Raw climate~~Climate~~ model output from 20~~15~~ models was obtained from the CMIP5 data archive (http://cmip-pcmdi.llnl.gov/cmip5/data_portal.html) and the World Data~~Date~~ Center for Climate site (http://cera-www.dkrz.de/WDCC/ui/Index.jsp). The monthly temperature data is aggregated to the global annual mean level using code developed using CDOs (see CDO 2018: Climate Data Operators. Available at http://www.mpimet.mpg.de/cdo). The long-term drift is removed from the CMIP5 model data by subtracting the linear trend from the corresponding pre-industrial control run (Gupta et al., 2013)~~(Gupta et al. 2013)~~. Table S3~~S2~~ provides the CMIP5 modeling centre name and the model name from Figure 4.

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Table S3 CMIP5 and SCM model information

Centre(s)	Model name
Beijing Climate Center (BCC) **China**	BCC-CSM1.1
Canadian Centre for Climate Modelling and Analysis (CCCma) **Canada**	CanESM2
National Center for Atmospheric Research **USA**	CCSM4
Centre National de Recherches Météorologiques, Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique (CNRM-CERFACS) **France**	CNRM-CM5-2
Commonwealth Scientific and Industrial Research Organization/Queensland Climate Change Centre of Excellence **Australia**Institut Pierre Simon Laplace (IPSL) **France**	CSIRO-Mk3-6-0IPSL-CM5A-LR
	IPSL-CM5A-MR
	IPSL-CM5B-LR
Institute of Atmospheric Physics, Chinese Academy of Sciences (LASG-CESS) **China**	FGOALS-g2
Geophysical Fluid Dynamics Laboratory (NCAR; NSF-DOE-NCAR) **USA**	GFDL-CM3 GFDL-ESM2G GFDL-ESM2M
NASA/GISS (Goddard Institute for Space Studies; NASA-GISS) **USA**	GISS-E2-H GISS-E2-R
Institut Pierre Simon Laplace (IPSL) **France**	IPSL-CM5A-LR IPSL-CM5A-MR IPSL-CM5B-LR
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology (MIROC)	MIROC-ESM MIROC5

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Japan	
Max Planck Institute for Meteorology (MPI-M) **Germany**	MPI-ESM-MR
	MPI-ESM-P
Meteorological ResearchNASA/GISS (Goddard Institute for Space Studies; NASA-GISS) **JapanUSA**	MRI-CGCM3GISS-E2-H
Norwegian Meteorological Institute **Norway**	NorESM1-MGISS-E2-R
Geophysical Fluid Dynamics Laboratory (NCAR; NSF-DOE-NCAR) **USA**	GFDL-CM3
	GFDL-ESM2G

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S3.1 Abrupt 4xCO_2 concentration step response from Geoffroy et al. (2013)

Conducting impulse tests with complex models is computationally expensive, illustrated by the few studies employing this technique to understand the responses of models. We cite the Sand et al. (2016) study that specifically investigated NorESM's response to black carbon (BC) perturbations (Sand et al., 2016). Another study by Yang et al. (2019) conducted similar BC perturbations in CESM (Yang et al., 2019). Other stylized CMIP5 experiments, such as the 1% CO_2 concentration experiment, are not included in our comparison because we do not consider them to be impulse response tests. It is not possible to cleanly extract the impulse response from the 1% experiments. The CMIP5 4xCO_2 concentration step experiment is mathematically related to impulse responses, so are a reasonable comparison, particularly because these are the largest suite of such tests conducted in complex models, which is the reason we highlight these results in the paper.

Geoffroy et al. (2013) reported the 4xCO_2 concentration step temperature change relative to the 150-year temperature mean from the corresponding pre-industrial control run. For comparison to the simple models, we report the drift corrected 4xCO_2 concentration step temperature change relative to the start of the 4xCO_2 concentration run. Therefore, there will be a difference in the temperature reported.

Figure S3 shows the global mean temperature response from the $4xCO_2$ concentration step experiment for the 20 CMIP5 models used in our comparison following the Geoffroy et al. (2013) procedure of reporting the $4xCO_2$ concentration step temperature change relative to the 150-year temperature mean from the corresponding pre-industrial control run. The responses reported in Figure S3 are consistent with Geoffroy et al. (2013).

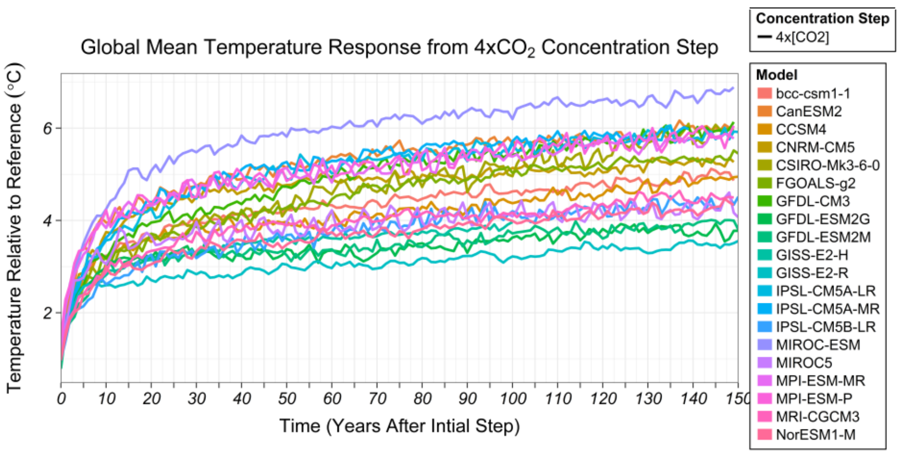

Figure S3 *Global mean temperature response from $4xCO_2$ concentration step in CMIP5 models following the Geoffroy et al. methodology.*

S4 Sensitivity Experiments in MAGICC 5.3

We conduct two sensitivity experiments to illustrate there is little impact of these choices on the model responses: (1) perturb CO_2 emissions in different years and (2) perturb CO_2 emissions at different levels in 2015.

S4.1 Impact of Changes to the Years of Emission Impulses

We test CO_2 emissions perturbations in different years from the default 2015 used in the main text. Figure S4~~**Error! Not a valid bookmark self-reference.**~~ shows the global mean temperature response normalized by the 2010 global mean temperature response from a CO_2 emissions pulse in MAGICC 5.3. We found a maximum of 0.028°C/PgC difference in the response in MAGICC 5.3 and, therefore, carried out the remainder of the experiment in 2015, avoiding model base years.

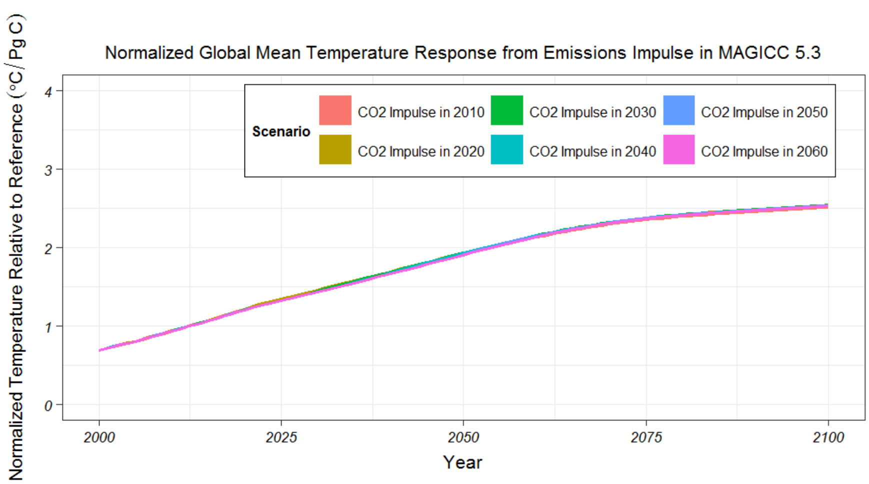

Figure S4 *Normalized global mean temperature response from CO_2 emissions impulses in MAGICC 5.3 carried out in different years.*

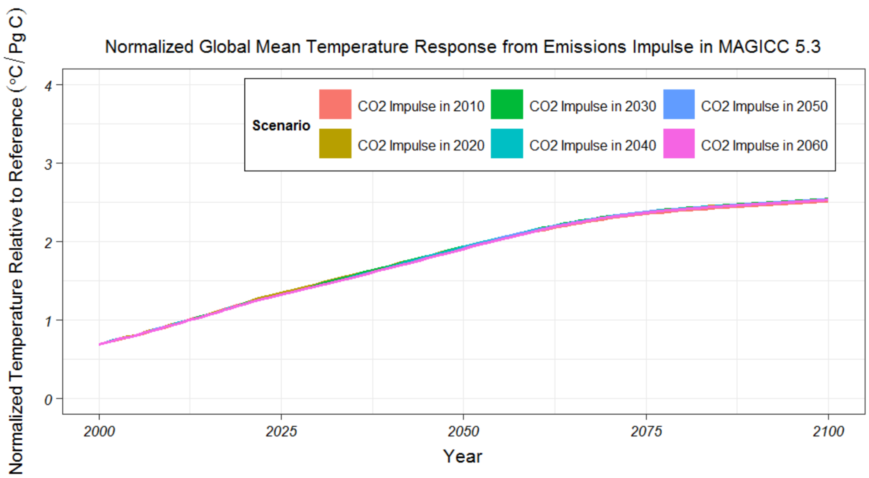

Figure S1 *Normalized global mean temperature response from CO_2 emissions impulses in MAGICC 5.3 carried out in different years.*

S4.2 Impact of Emissions Pulses Size on Temperature Response

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In the main text, we carried out annual emissions perturbations equivalent to doubling the value in 2015 to avoid model base years.   shows the global mean temperature response normalized by the perturbation size for different CO_2 perturbation sizes in 2015 in MAGICC 5.3. We found there was a maximum difference of 0.0015°C/PgC, and thus we continued our experiments using only one perturbation value.

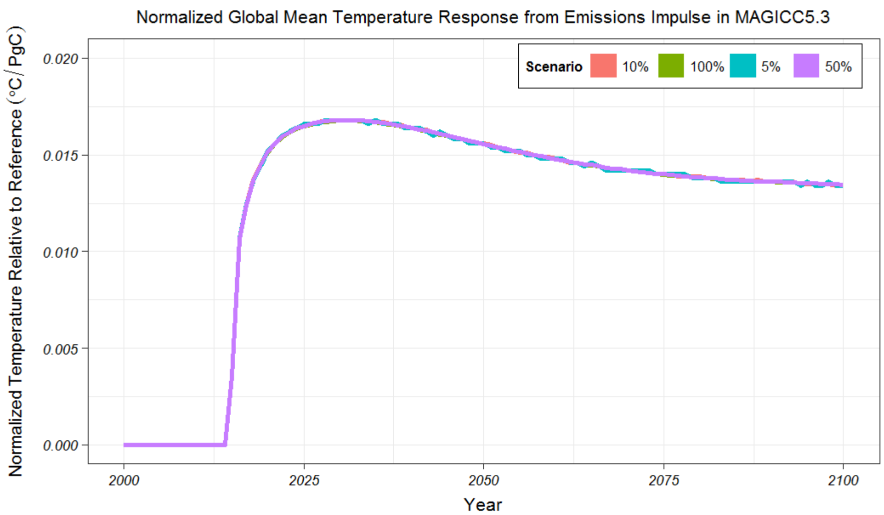

Figure S5 *Normalized global mean temperature response from different sized CO_2 emissions impulses in MAGICC 5.3 in 2015.*

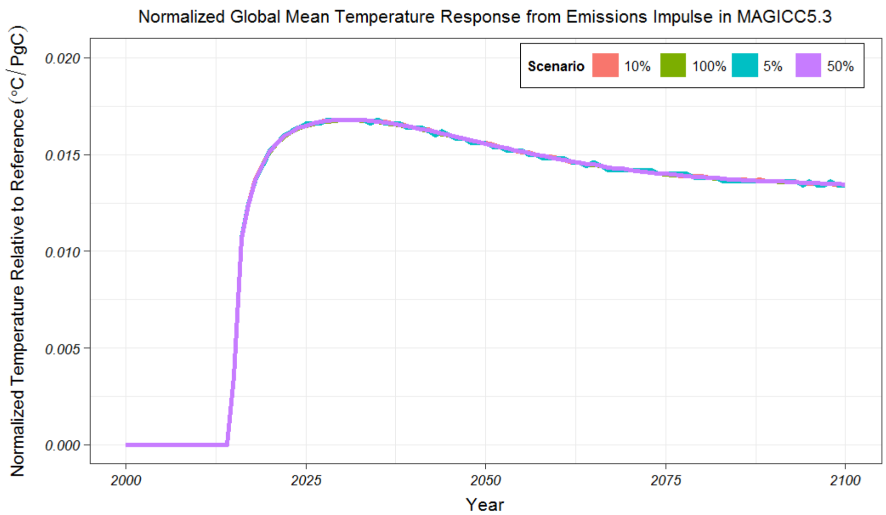

Figure S2 *Normalized global mean temperature response from different sized CO_2 emissions impulses in MAGICC 5.3 in 2015.*

S5 Adjusted Total Forcing Response

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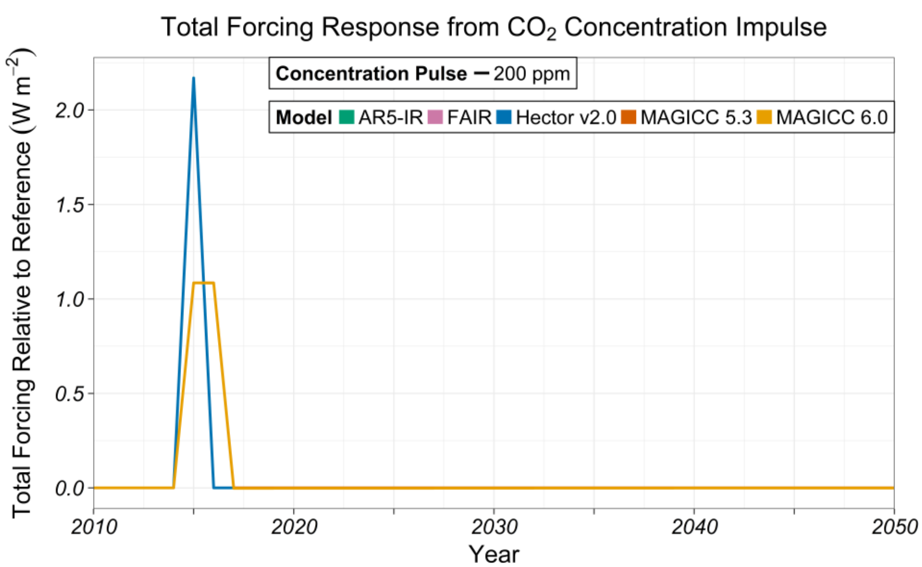
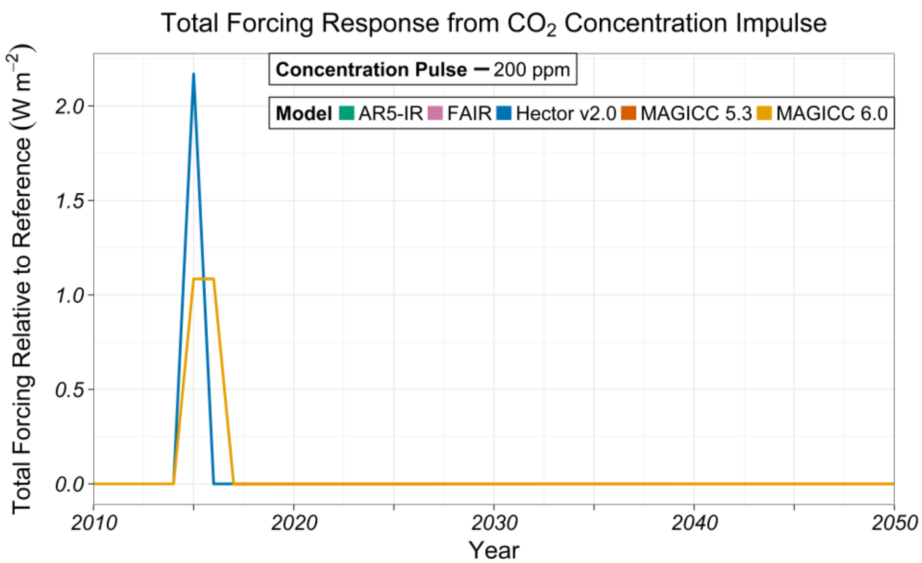
We found that MAGICC 5.3, MAGICC 6.0, and Hector v2.0 respond similarly to a CO_2 concentration impulse, with differences in the forcing and temperature responses arising from the treatment of time within each model. Hector v2.0, for example, reads in annual average ~~end-of-year~~ emissions and carries out calculations ~~of concentration, forcing, and temperature~~ using that same classification of time. MAGICC 5.3 and MAGICC 6.0 read in annual~~end-of-year~~ emissions and interpolate to obtain mid-year and end-of-year values and uses those internally to calculate concentration, forcing, and temperature at mid-year values, and successively reports temperature at the end-of-~~-~~year. This change in the timing affects~~effects~~ the impulse response by distributing the pulse over more time periods. Here, we demonstrate the impact of the~~offer an~~ adjustment for the forcing response to a CO_2 concentration impulse.





530 **Figure S6** *Total forcing response from a CO_2 concentration impulse in SCMs. Three comprehensiveAll three SCMs have a collinear response (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue). The responses are co-linear past 2016., AR5-IR – green, FAIR – pink).*

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Due to the differences in model treatment of time, we offer a correction to the forcing in two of the SCMs. MAGICC 5.3 and MAGICC 6.0 calculate forcing in mid-year, while Hector v2.0 reports forcing at the end of a year. The result is a broadened impulse response peak in both versions of MAGICC, compared to Hector v2.0. The total forcing response from both version of MAGICC, however, can be adjusted with the following equation:

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$$F_i = (2xf_i) - f_{i-1} \qquad (118)$$

where F_i is the adjusted forcing, f_i is the unadjusted forcing at the current time step, and f_{i-1} is the unadjusted forcing at the previous time step.

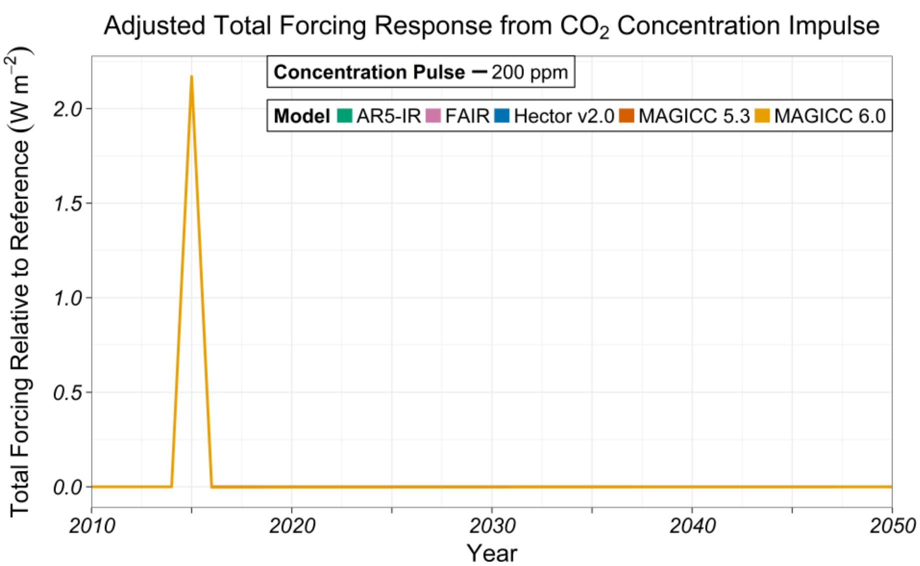


Figure S7 *Total forcing response from a CO_2 concentration impulse in SCMs. All three SCMs have a collinear response (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, AR5-IR – green, FAIR –pink).*

shows the total forcing response adjusted from mid-year reporting, to end-year reporting using equation (SI. Eqn. S118). We can also apply this adjustment to the BC impulse, however, the

MAGICC 6.0 distribution is larger in this case because MAGICC 6.0 annual emissions are interpolated to produce end-of-year and intermediate values. An annual emissions pulse is effectively spread over two model years. In the main paper, we report the integrated response because over these periods, the timing of the internal model calculations has minimal impact on the model results. Additional integrated model responses are in S9.~~.~~

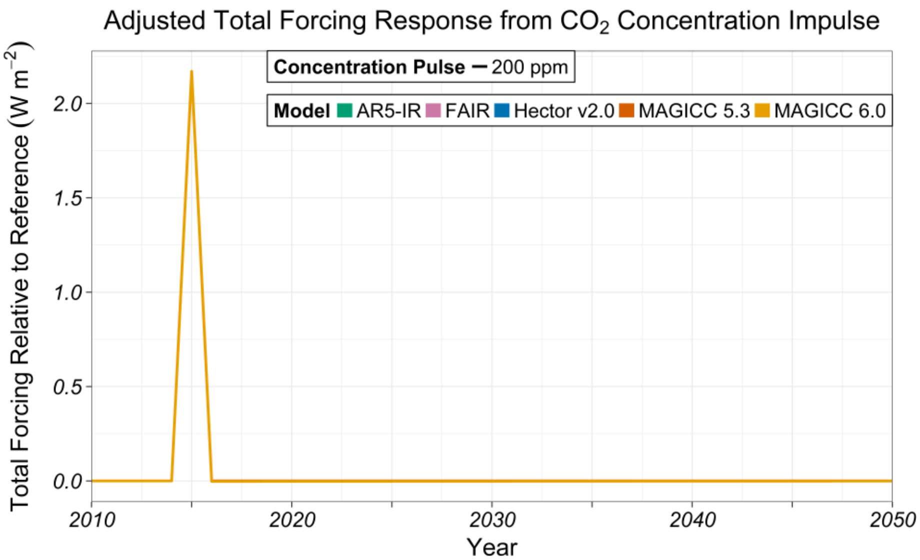
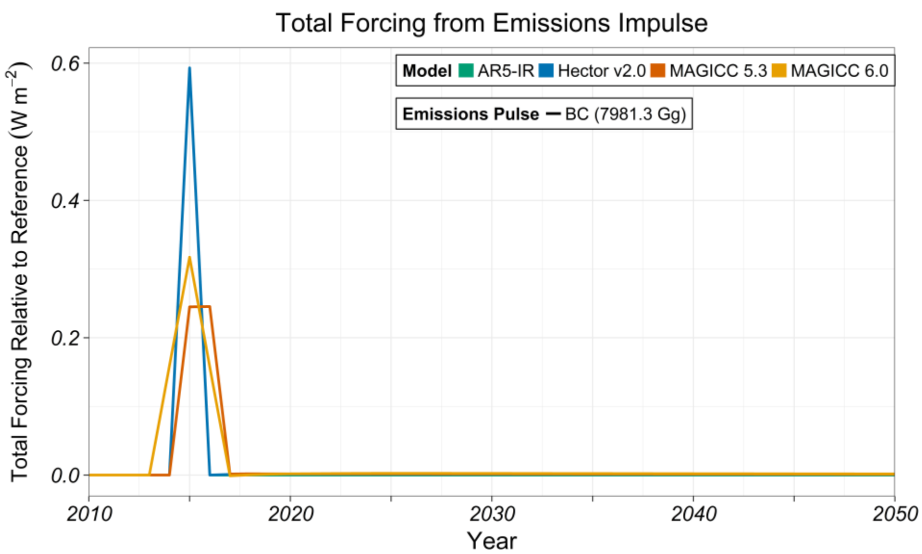


Figure S4 *Total forcing response from a CO_2 concentration impulse in SCMs. All three SCMs have a collinear response (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, AR5-IR – green, FAIR – pink).*

S6 Total Forcing Response from BC Emissions Impulse

We see in Figure S8 that the model responses to a pulse of BC have similar patterns of instantaneous behavior seen in FigureFig. 1 from the CO_2 concentration pulse. In general, the models behave similarly in response to a BC pulse; Hector v2.0 and AR5-IR have a collinear response, while MAGICC 6.0 distributes the BC emissions pulse over 3 years.



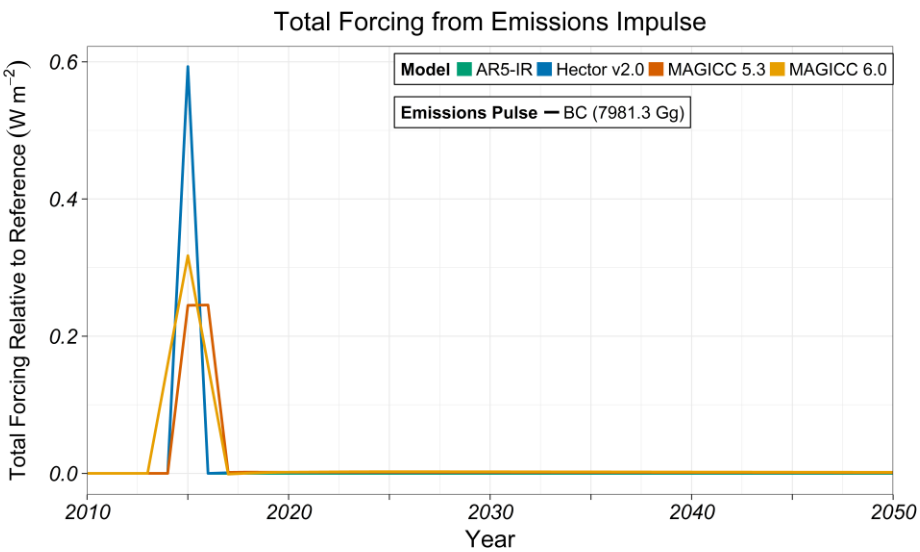


Figure S8 *Total forcing response from a BC emissions perturbation in SCMs (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, AR5-IR-green). AR5-IR and Hector v2.0 are collinear.*

S7 CO_2 Concentration Responses from Emissions Impulses

Figure S9 shows the CO_2 concentration responses from a BC and CH_4 emissions pulse. Every model response shows an eventual CO_2 concentration increases from a BC impulse; a feedbacksecondary effect from the temptemperature increase impact on the carbon cycle. From a CH_4 and BC emissions pulse, the CO_2 concentration response is stronger in MAGICC 6.0, followed by MAGICC 5.3 and Hector v2.0. MAGICC 6.0, however, shows an initial decrease in CO_2 concentration response from the BC pulse.

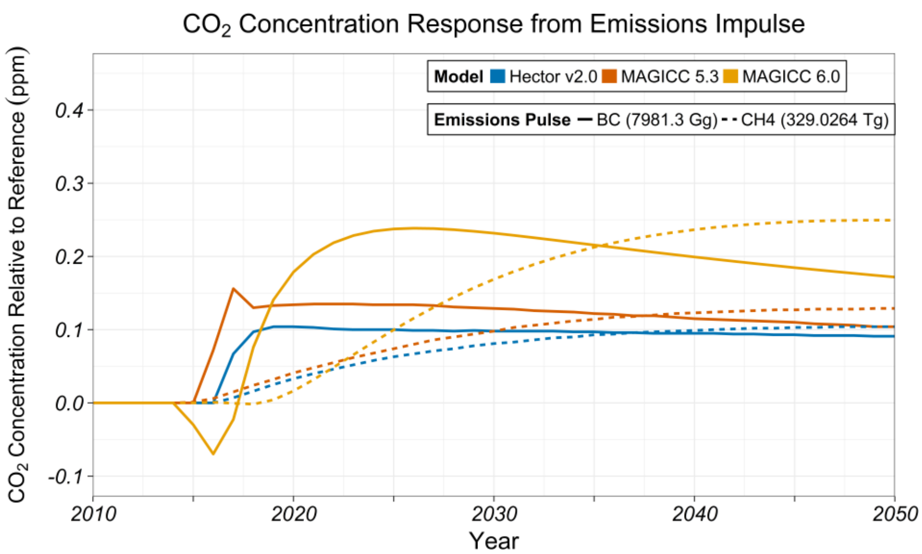


Figure S9 *CO_2 concentration response from CH_4 and BC emissions perturbation (B) in SCMs (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue) illustrating the carbon-cycle feedbacks present in each model.*

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Figure S9 also shows that CH_4 emission perturbations impact CO_2 concentration within both versions of MAGICC. The discrepancy between the MAGICC and Hector responses is partly due to CH_4 oxidation in MAGICC 5.3. The MAGICC 6.0 response is larger in Figure S9 presumably due to feedback effects in~~because of~~ the model~~temporal distribution of the pulse~~, however, the general shape of the response is similar to the other two SCMs.

AR5-IR is notably absent from Figure S9 because, in this IRF model, the CO_2 concentrations are not affected by changing temperature (Millar et al., 2017). Rising temps in general and including temp changes due to CH_4 and BC emissions perturbations. FAIR v1.0 model (Millar et al., 2017) is absent from ~~because, in this IRF, the CO_2 concentration is not affected by rising temperature or CO_2 accumulation from BC or CH_4 emissions perturbations (Millar et al. 2017). Similarly, the FAIR model (Millar et al. 2017) is absent from~~ Figure S9 because the model does not report out the internally-calculated forcing response.~~.~~ The CO_2 concentration response to a CO_2 emissions impulse in FAIR can be seen in .

The CH_4 chemistry components in Hector v2.0 and MAGICC 5.3 BC-OC are nearly identical, accounting for the similarities between these two SCMs responses (Hartin et al., 2015)~~(C. A. Hartin et al. 2015)~~. MAGICC 5.3, however, includes CH_4 oxidation to CO_2, which might account for this response difference. To test this, Figure S10 shows the CO_2 concentration response from emissions impulse in SCMs. MAGICC 5.3 is shown with and without CH_4 oxidation included for a clearer comparison of the Hector v2.0 response. With the CH_4 oxidation turned off, the MAGICC 5.3 BC-OC response is similar to Hector v2.0 with only a slight difference after 2025.

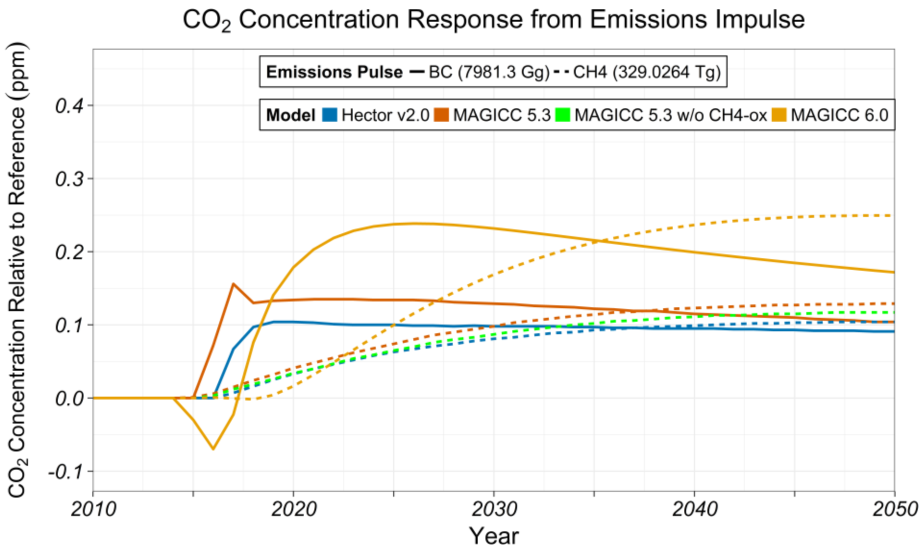

Figure S10 *CO_2 concentration response from emissions impulse in SCMs. MAGICC 5.3 is shown with and without CH_4 oxidation included (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue)..*

S8 Model Responses out to 2300

- show the CO_2 concentration response, total forcing response, and global mean temperature response from an emissions impulse, respectively, to the end of the model period equal to 2300.

S8.1 CO_2 Concentration Response to a CO_2 Emissions Pulse

shows the CO_2 concentration response from a CO_2 emissions pulse in the SCMs out to 2300. We see that the SCMs respond similarly to this perturbation, with the exception of the stylized SCM, FAIR, which has a weaker response.

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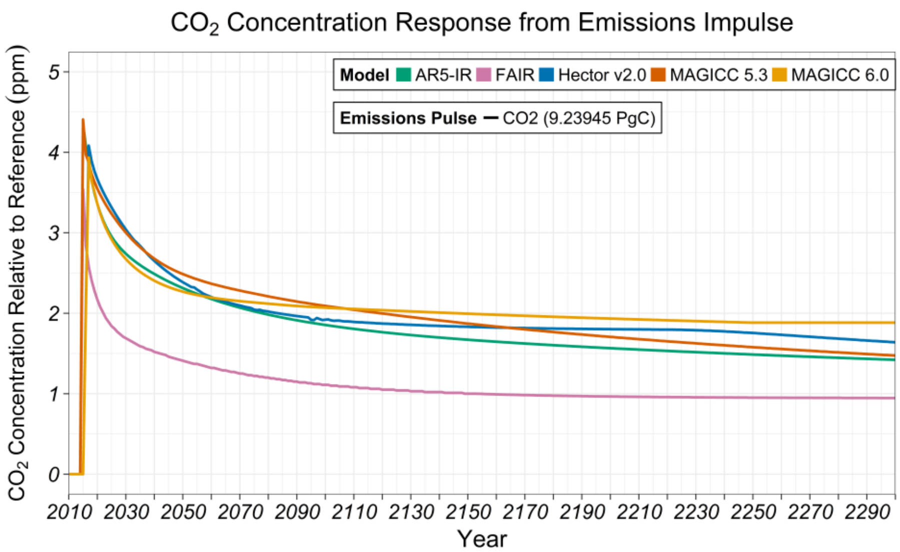

Figure S11 *Carbon dioxide concentration response from a CO_2 emissions pulse in SCMs (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, AR5-IR – green, FAIR - pink).*

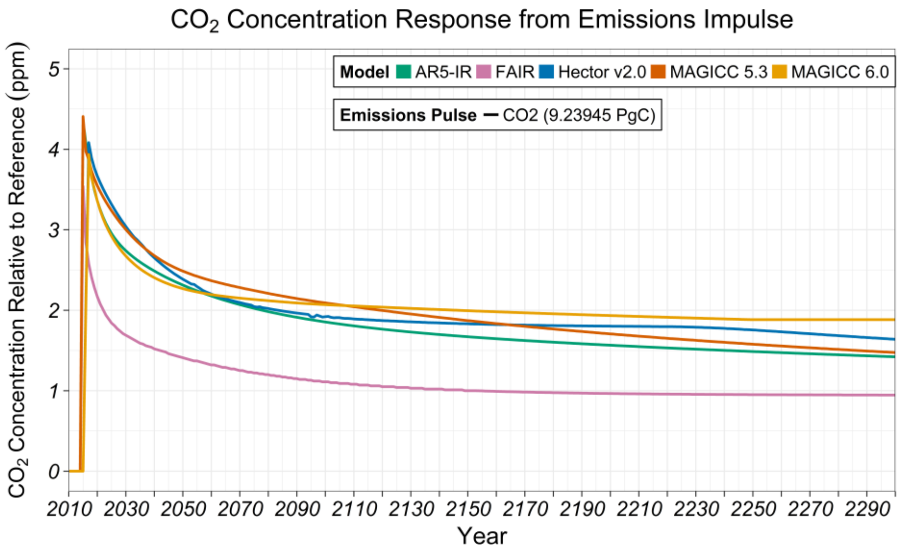

Figure S8 *Carbon dioxide concentration response from a CO_2 emissions pulse in SCMs (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, AR5-IR – green, FAIR - pink).*

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S8.2 CH_4 Concentration Response from CH_4 Emissions Pulse

shows the CH_4 concentration response from a CH_4 emissions pulse in the comprehensive SCMs out to 2300. The stylized SCMs do not report CH_4 concentrations. We see that the comprehensive SCMs behave similarly in their response to this perturbation, especially after 2050 when the response tends towards 0 ppb.

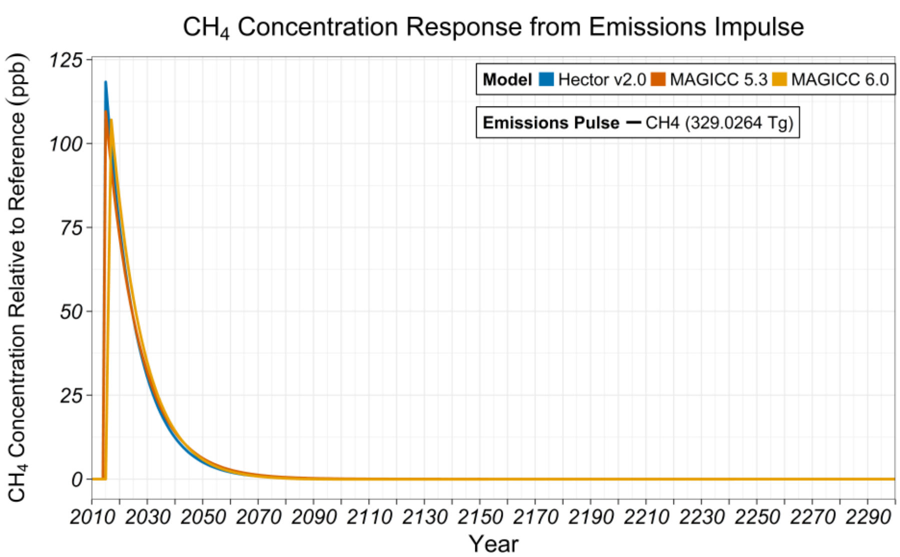
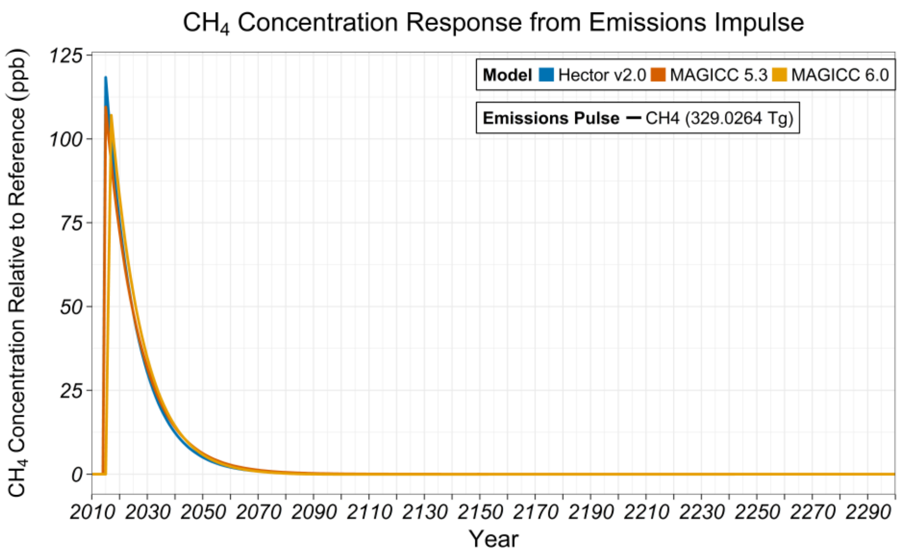


Figure S12 *Methane concentration response from a CH_4 emissions pulse in SCMs out to 2300 (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue).*

635



~~**Figure S9** *Methane concentration response from a CH_4 emissions pulse in SCMs out to 2300 (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue).*~~

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S8.3 CO_2 Concentration Response to a BC or CH_4 Emissions Pulse

shows the CO_2 concentration response from a CH_4 and BC emissions perturbations in the SCMs out to 2300. We see that the SCMs behave differently across the entire time series. Hector v2.0 appears to changechanges state after 2225., a feature being investigated by the modeling team who originally calibrated the model out to 2300.

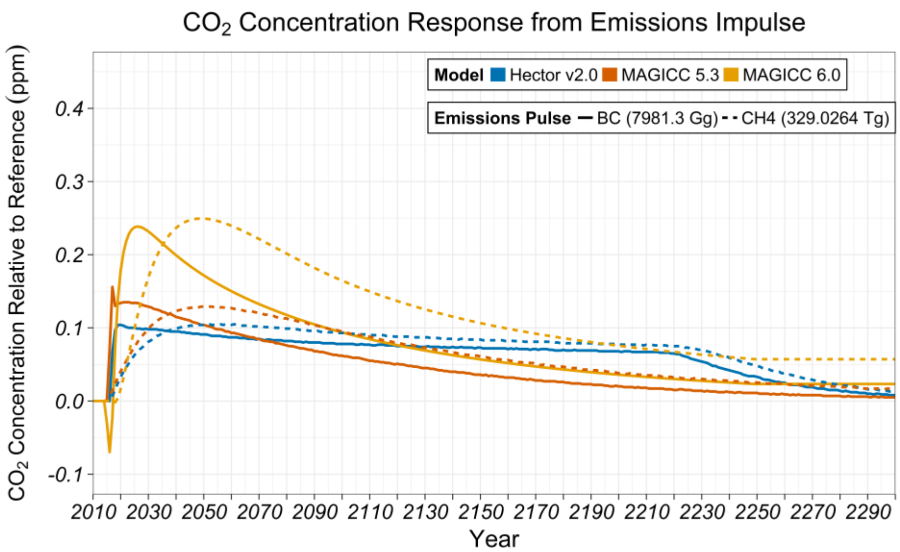


Figure S13 *CO_2 concentration response from emissions perturbations in SCMs out to 2300 (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue).*

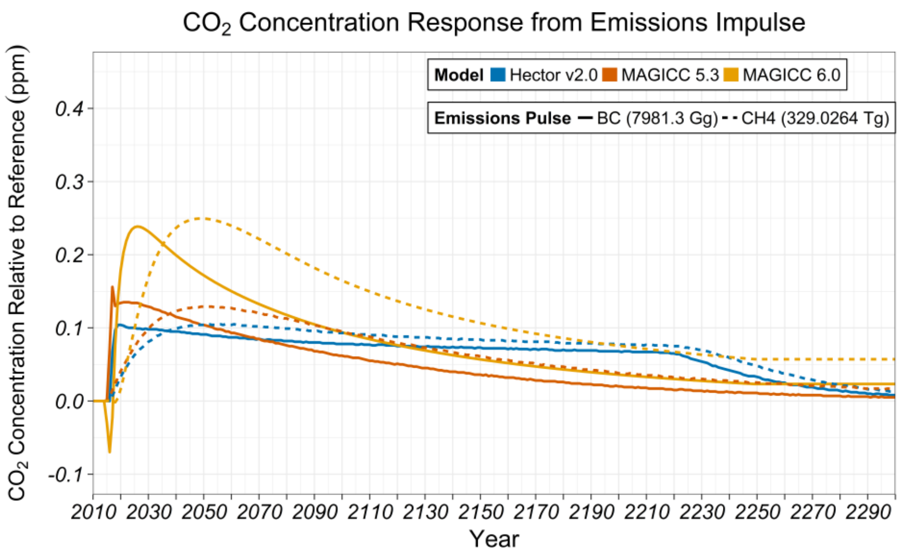


Figure S10 *CO_2 concentration response from emissions perturbations in SCMs out to 2300 (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue).*

S8.4 Total Forcing Response to a CO_2 or CH_4 Emissions Pulse

We report the total forcing response from the models, rather than the individual species' forcing responses for comparability. AdditionallyThis has little impact on the results because, in the case of the non-CO_2 species, the total forcing is similar to the individual forcing responses because forcing is dominated by the forcing from the perturbed speciesCO_2 response, which is removed by subtracting the reference case.

shows the total forcing response from a CH_4 and CO_2 emissions perturbations in the SCMs out to 2300. FAIR does not report total forcing.

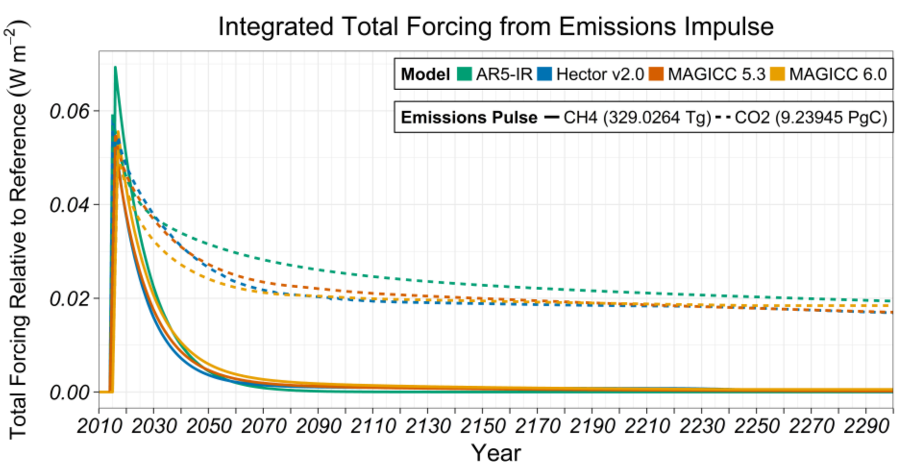


Figure S14 *Total forcing response from emissions perturbations in SCMs out to 2300 (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, AR5-IR – green).*

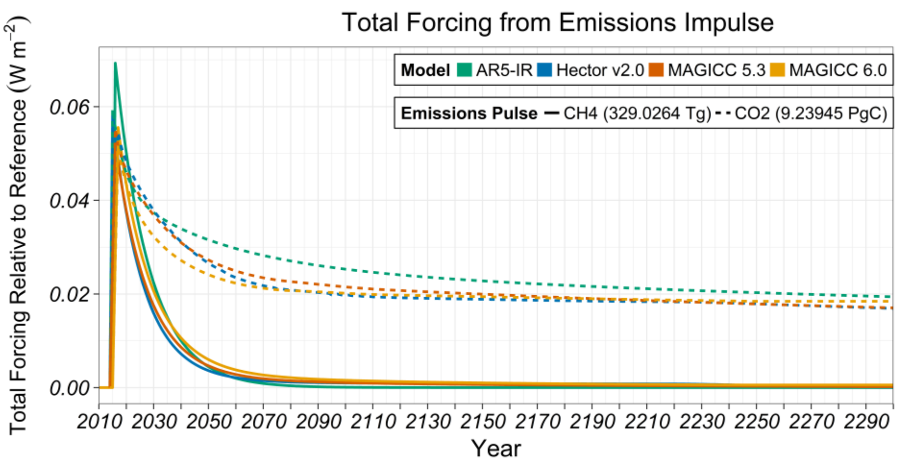


Figure S11 *Total forcing response from emissions perturbations in SCMs out to 2300 (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, AR5-IR – green).*

S8.5 Global Mean Temperature Response to a CH_4 or CO_2 Emissions Pulse

shows the temperature response from a CH_4 and CO_2 emissions perturbations in the SCMs out to 2300. We see that most of the SCM responses differ slightly immediately following the perturbation, but converge over time. AR5-IR has a stronger response than the other SCMs immediately following the perturbation. More details are included in the main paper.

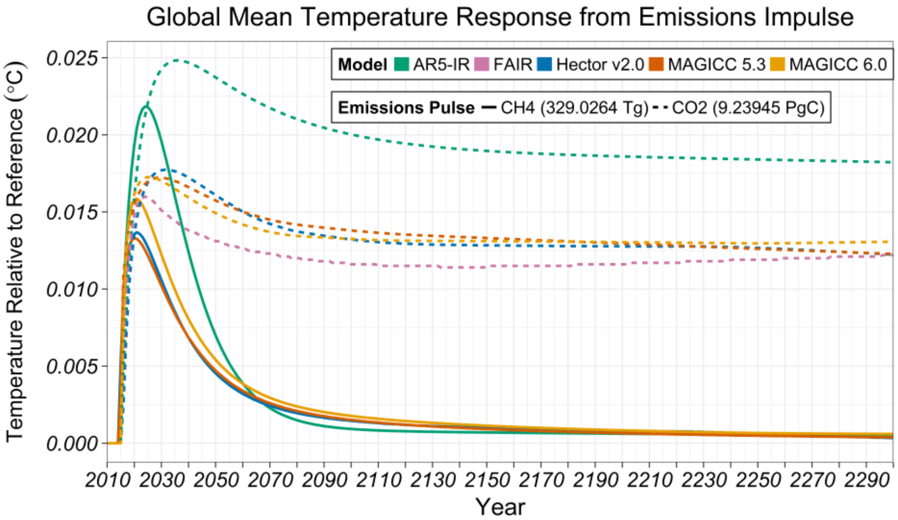
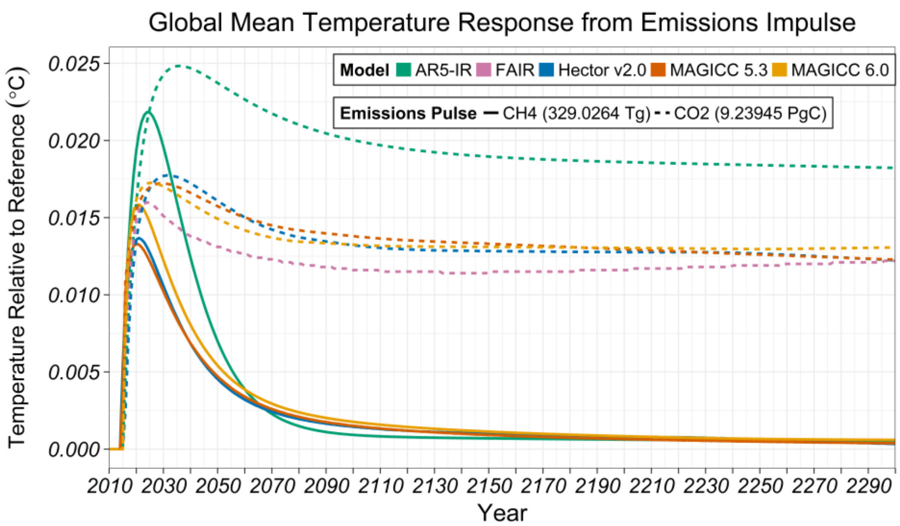


Figure S15 *Global mean temperature response from emissions perturbations in SCMs out to 2300 (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, AR5-IR – green, FAIR - pink).*



~~**Figure S12** *Global mean temperature response from emissions perturbations in SCMs out to 2300 (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, AR5-IR – green, FAIR - pink).*~~

S9 Time Integrated Responses

Figure S16S13 – Figure S21S18 shows the integrated forcing and temperature response for the full suite of experiments to the end of the model period. The data tables in this section provide numerical data (rounded to three significant figures) supporting the integrated forcing or temperature response figures. The data tables also include percent differences found using the following formula:

$$Percent\ Difference_{i,t} = \left(\frac{Model\ response_{i,t} - Average\ Comprehensive\ Model\ Response_{t}}{Average\ Comprehensive\ Model\ Response_{t}}\right) \times 100 \qquad (129)$$

where *t* is the time horizon and *i* is the individual model. A positive percent difference indicates that the model response is stronger than the average comprehensive model response, while a negative value indicates the model response was weaker than the average comprehensive model response.

S9.1 Time Integrated Responses from a CO_2 Concentration Impulse

Figure S16S13 shows the time--integrated total forcing response from a CO_2 concentration impulse.

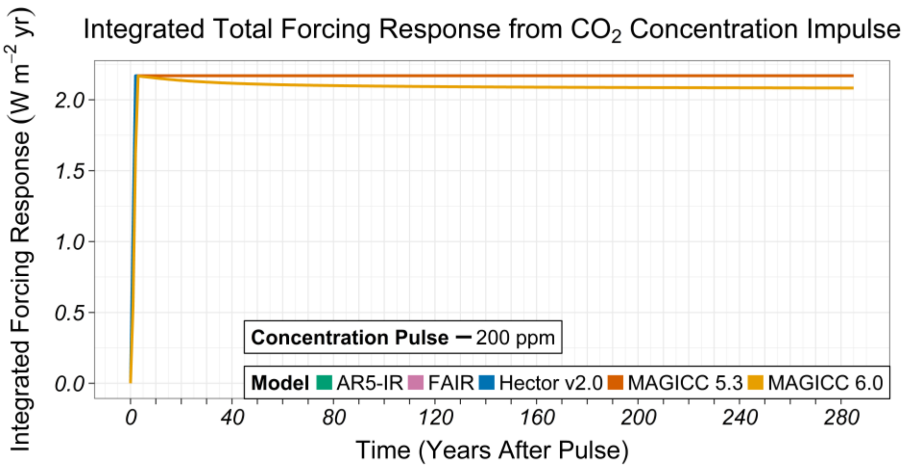


Figure S16 *Time--integrated forcing response from a CO_2 concentration impulse for the SCMs to the end of the model period (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, AR5-IR – green, FAIR - pink).*

Figure S17S14 shows the time--integrated global mean temperature response from a CO_2 concentration impulse to the end of the model period. We see that the comprehensive SCMs respond similarly, while AR5-IR has a stronger response and FAIR, a slightly weaker response. The associated values time integrated temperature responses are in Table S4S3.

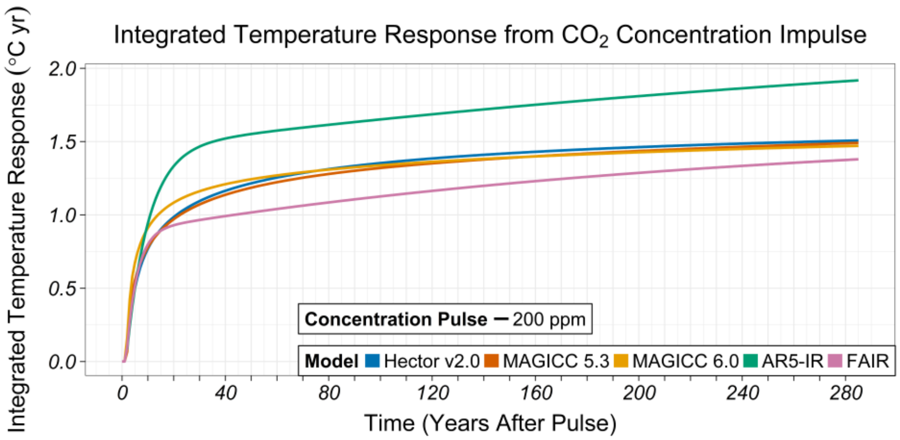


Figure S17 *Time-integrated temperature response from a CO_2 concentration impulse for the SCMs to the end of the model period (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, AR5-IR – green, FAIR - pink).*

Table S4 Integrated Temperature Responses from a CO_2 Concentration Impulse in the SCMs

Time After Pulse	Integrated Temperature Response (°Cyr)						Percent Difference from Comprehensive SCMs Average (%)				
	MAGICC 5.3 BC-OC	**MAGICC 6.0**	**Hector v2.0**	**FAIR**	**AR5-IR**	**Average of Comprehensive SCMs**	**MAGICC 5.3 BC-OC**	**MAGICC 6.0**	**Hector v2.0**	**FAIR**	**AR5-IR**
10	0.85	0.98	0.85	0.87	0.24	0.90	-4.79	9.59	-4.79	-3.57	-73.5
20	1.00	1.11	1.02	0.94	1.10	1.04	-4.25	6.29	-2.04	-9.80	5.33
50	1.20	1.25	1.22	1.02	1.39	1.22	-2.07	2.26	-0.19	-16.6	13.7
100	1.32	1.34	1.35	1.13	1.65	1.34	-1.25	0.25	1.00	-15.5	23.4
150	1.39	1.39	1.42	1.13	1.74	1.40	-0.71	-0.71	1.43	-19.3	24.3
285	1.46	1.47	1.51	1.38	1.92	1.48	-1.31	-0.63	1.94	-6.71	29.8

S9.2 Time Integrated Responses from a CO_2 Emissions Impulse

Figure S18~~S15~~ and Figure S19 show~~S16 shows~~ the integrated forcing (Table S5~~S4~~) and temperature response (Table S6~~S5~~) for the CO_2 emissions impulse experiment to the end of the model period, respectively. The numerical data is shown~~shows~~ in ~~the~~ Table S5~~S4~~ and Table S6.~~S5.~~

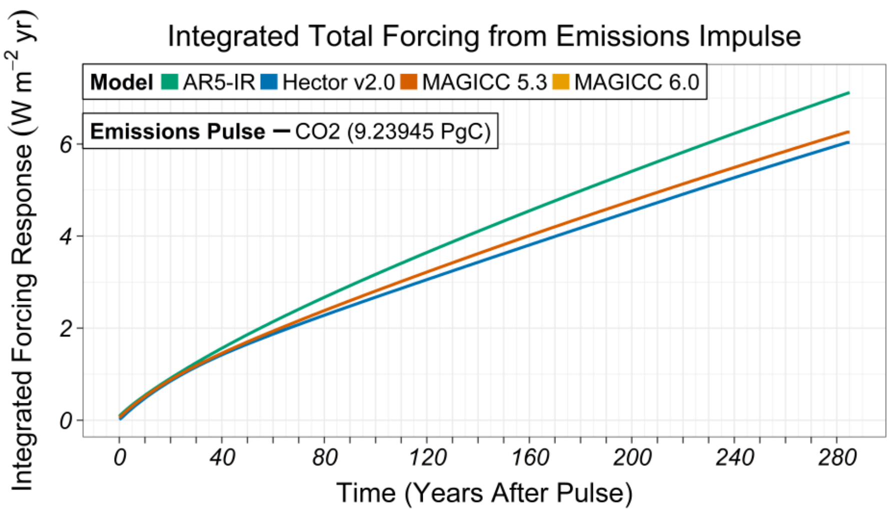
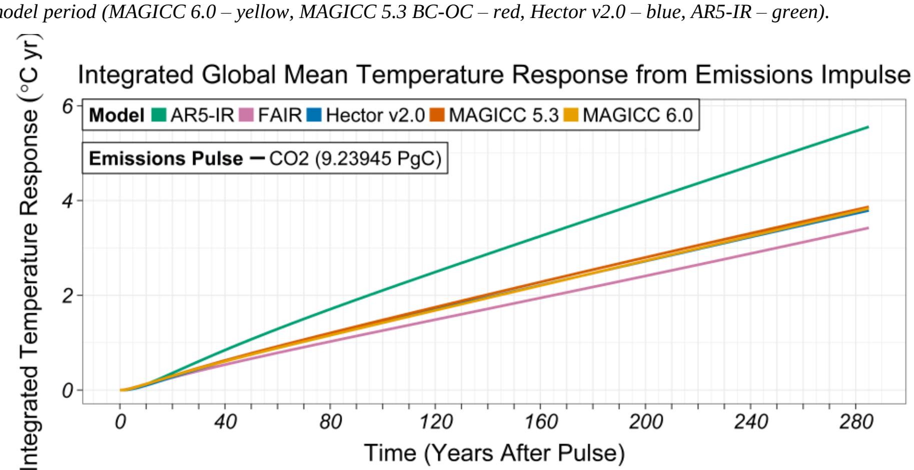


Figure S18 *Time-integrated total forcing response from a CO_2 emissions impulse for the SCMs to the end of the model period (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, AR5-IR – green).*



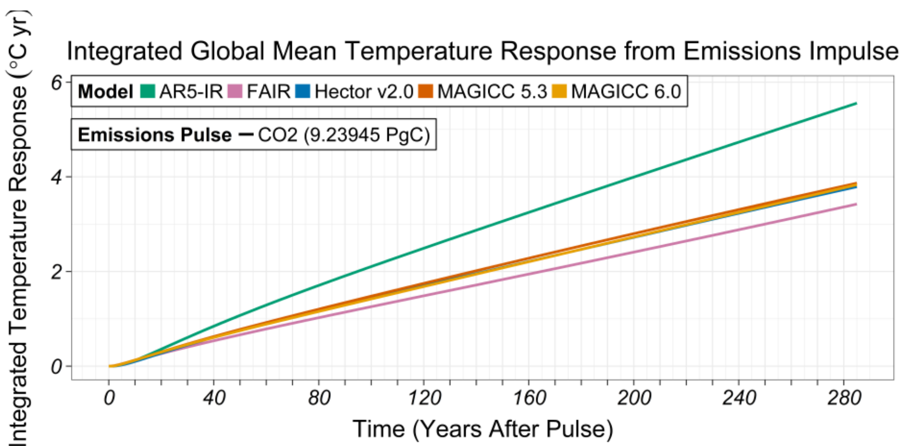


Figure S19 *Time-integrated temperature response from a CO_2 emissions impulse for the SCMs to the end of the model period (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, AR5-IR – green, FAIR - pink).*

Table S5 Integrated Forcing Responses from a CO_2 Emissions Impulse in the SCMs

Time After Pulse	Integrated Forcing Response ($Wm^{-2}yr$)					Percent Difference from Comprehensive SCMs Average (%)			
	MAGICC 5.3 BC-OC	**MAGICC 6.0**	**Hector v2.0**	**AR5-IR**	**Average of Comprehensive SCMs**	**MAGICC 5.3 BC-OC**	**MAGICC 6.0**	**Hector v2.0**	**AR5-IR**
10	0.51	0.43	0.48	0.54	0.47	8.67	-9.51	0.85	14.38
20	0.88	0.75	0.85	0.91	0.82	6.39	-9.38	2.99	10.63
50	1.70	1.48	1.65	1.86	1.61	5.63	-8.28	2.65	15.38
100	2.81	2.50	2.67	3.17	2.66	5.52	-5.96	0.44	19.13
150	3.82	3.47	3.62	4.32	3.63	4.97	-4.52	-0.45	18.87
285	6.26	5.97	6.03	7.12	6.09	2.79	-1.89	-0.90	16.98

Table S6 Integrated Temperature Responses from a CO_2 Emissions Impulse in the SCMs

Time After Pulse	Integrated Temperature Response (°Cyr)						Percent Difference from Comprehensive SCMs Average (%)				
	MAGICC 5.3 BC-OC	MAGICC 6.0	Hector v2.0	FAIR	AR5-IR	Average of Comprehensive SCMs	MAGICC 5.3 BC-OC	MAGICC 6.0	Hector v2.0	FAIR	AR5-IR
10	0.16	0.16	0.13	0.14	0.18	0.15	6.81	5.49	-12.31	-5.71	20.66
20	0.33	0.33	0.31	0.29	0.42	0.32	2.99	1.44	-4.43	-9.38	29.90
50	0.81	0.78	0.79	0.69	1.00	0.79	1.86	-1.69	-0.17	-13.07	26.15
100	1.50	1.45	1.46	1.27	1.93	1.47	2.16	-1.59	-0.57	-13.51	31.44
150	2.17	2.10	2.10	1.85	2.86	2.12	2.20	-1.10	-1.10	-12.87	34.69
285	3.87	3.85	3.80	3.44	5.87	3.84	0.83	0.17	-1.00	-10.38	52.93

S9.3 Time Integrated Responses from a CH_4 Emissions Impulse

Figure S17 and Figure S18 show~~shows~~ the integrated forcing (Table S6) and temperature response (Table S7) for the CH_4 emissions impulse experiment to the end of the model period. The numerical data in Table S6 and Table S7.

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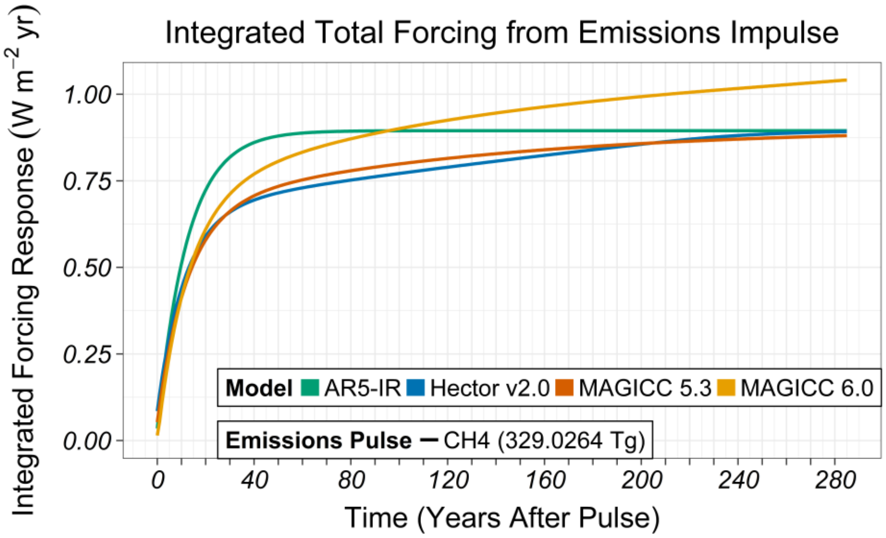

Figure S20 *Time-integrated total forcing response from a CH_4 emissions impulse for the SCMs to the end of the model period (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, AR5-IR – green).*

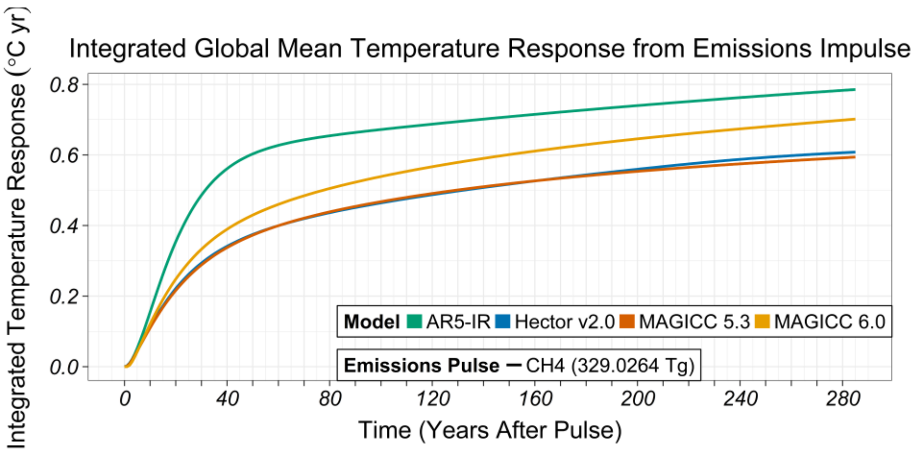

Figure S21 *Time--integrated temperature response from a CO_2 emissions impulse for the SCMs to the end of the model period (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, AR5-IR – green, FAIR - pink).*

Table S7 Integrated Forcing Responses from a CH_4 Emissions Impulse in the SCMs

Time After Pulse	**Integrated Forcing Response ($Wm^{-2}yr$)**					**Percent Difference from Comprehensive SCMs Average (%)**			
	MAGICC 5.3 BC-OC	**MAGICC 6.0**	**Hector v2.0**	**AR5-IR**	**Average of Comprehensive SCMs**	**MAGICC 5.3 BC-OC**	**MAGICC 6.0**	**Hector v2.0**	**AR5-IR**
10	0.41	0.41	0.44	0.51	0.42	-2.14	-2.14	4.28	21.1
20	0.58	0.61	0.59	0.72	0.59	-2.31	2.76	-0.45	21.9
50	0.73	0.81	0.72	0.88	0.75	-2.44	7.28	-4.84	16.9
100	0.80	0.90	0.77	0.89	0.82	-3.04	9.36	-6.32	8.63
150	0.83	0.95	0.82	0.89	0.87	-3.88	9.95	-6.07	3.03
285	0.88	1.04	0.89	0.89	0.94	-6.01	10.9	-4.94	-4.62

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Table S8 Integrated Temperature Responses from a CH_4 Emissions Impulse in the SCMs

Time After Pulse	**Integrated Temperature Response (°Cyr)**					**Percent Difference from Comprehensive SCMs Average (%)**			
	MAGICC 5.3 BC-OC	**MAGICC 6.0**	**Hector v2.0**	**AR5-IR**	**Average of Comprehensive SCMs**	**MAGICC 5.3 BC-OC**	**MAGICC 6.0**	**Hector v2.0**	**AR5-IR**
10	0.13	0.15	0.14	0.16	0.14	-4.26	7.10	-2.83	17.2
20	0.23	0.27	0.24	0.36	0.25	-5.56	8.68	-3.12	47.4
50	0.38	0.44	0.38	0.45	0.40	-5.03	9.55	-4.52	12.3
100	0.47	0.54	0.47	0.58	0.49	-4.54	9.88	-5.35	17.4
150	0.52	0.60	0.52	0.70	0.55	-4.99	10.2	-5.17	28.1
285	0.60	0.70	0.61	0.85	0.64	-6.20	10.5	-4.31	33.5

S9.4 Time Integrated Responses from a BC Emissions Impulse

Figure S19 and Figure S20 showshows the integrated forcing and temperature response for the BC emissions impulse experiment to the end of the model period, respectively. FAIR is not in this figure because weWe used FAIR v1.0, which only represented the response from CO_2 emissions. An updated version, FAIR v1.3, was recently released and includes non-CO_2 forcing. SI. Table S88 shows the integrated temperature response data.

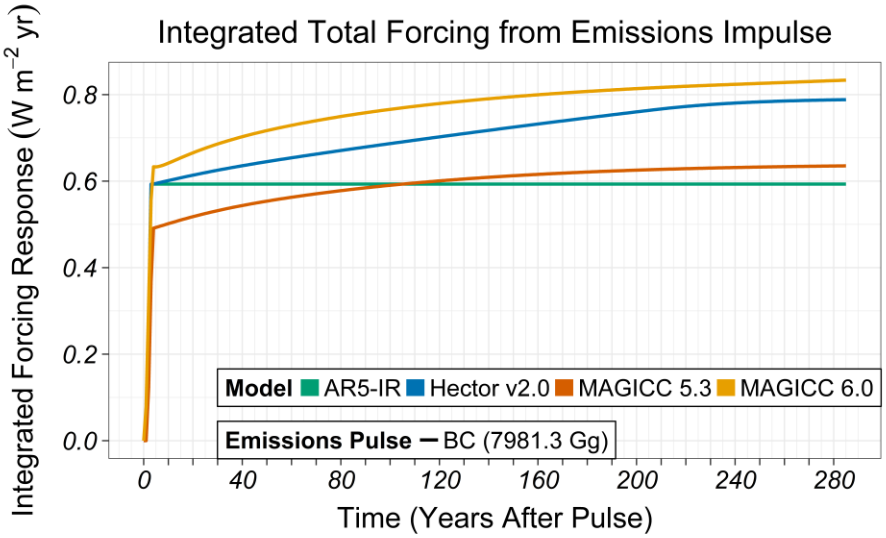

Figure S22 *Time-integrated total forcing response from a BC emissions impulse for the SCMs to the end of the model period (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, AR5-IR – green).*

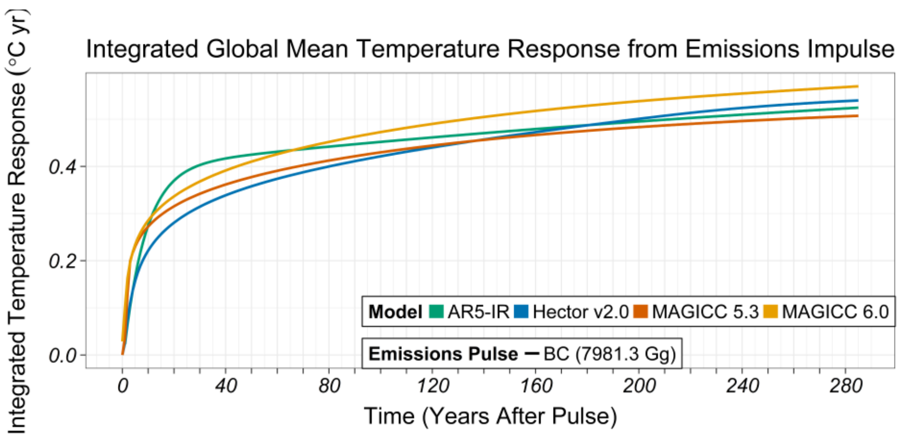

Figure S23 *Time-–integrated temperature response from a BC emissions impulse for the SCMs to the end of the model period (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, AR5-IR – green, FAIR - pink).*

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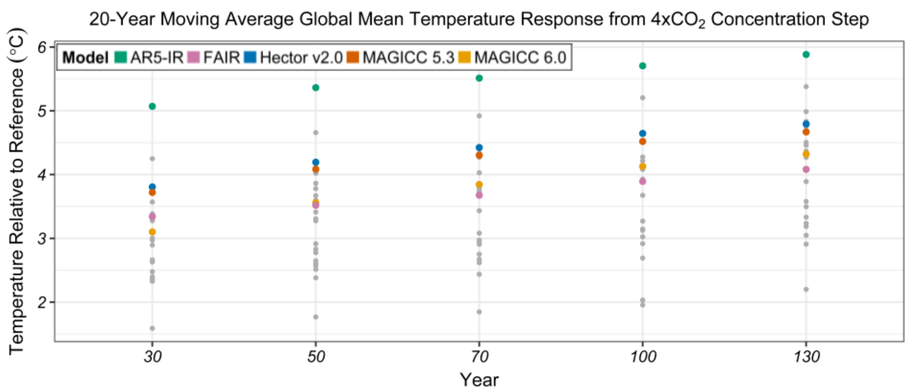
We see that Hector v2.0, which does not differentiate BC forcing over land and ocean and has a 9% weaker response 20 years after the pulse. MAGICC 6.0 diverges from the MAGICC 5.3 temperature response 20 years after the pulse. AR5-IR represents the temperature response from a BC perturbation as a simple exponential decay analogous to the greenhouse gas IRF, leading to a much stronger integrated temperature response (20%) 20 years after the pulse.

Table S9 Integrated Temperature Responses from a BC Emissions Impulse in the SCMs

Time After Pulse	Integrated Temperature Response (°Cyr)					Percent Difference from Comprehensive SCMs Average (%)			
	MAGICC 5.3 BC-OC	**MAGICC 6.0**	**Hector v2.0**	**AR5-IR**	**Average of Comprehensive SCMs**	**MAGICC 5.3 BC-OC**	**MAGICC 6.0**	**Hector v2.0**	**AR5-IR**
10	0.28	0.30	0.24	0.30	0.27	3.91	9.22	-13.1	11.0
20	0.32	0.34	0.29	0.38	0.32	1.13	8.12	-9.25	19.3
50	0.38	0.41	0.36	0.43	0.38	-1.22	7.43	-6.21	10.7
100	0.43	0.47	0.42	0.45	0.44	-2.68	7.12	-4.44	2.22
150	0.46	0.51	0.47	0.48	0.48	-3.80	6.76	-2.96	-0.92
285	0.51	0.57	0.54	0.53	0.54	-5.90	5.73	0.17	-2.56

S10 Temporal Response of SCMs Compared to 4xCO2 Concentration Step Experiment from CMIP5

Here we compare the 20-year moving average at time t=30, t= 50, t=70, t=100, and t=130 in the CMIP5 models and SCMs to show the temporal response of temperature. Hector v2.0 and MAGICC 5.3 have a faster response than the other SCMs and the majority of the complex models to an abrupt 4xCO_2 concentration step.



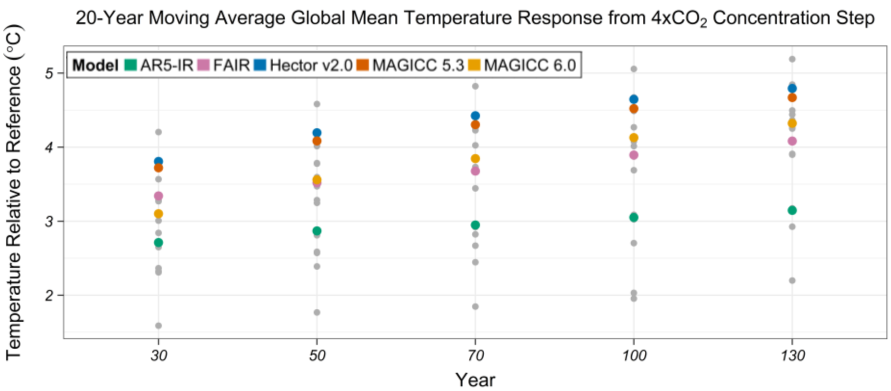


Figure S24 *20-Year moving average centered at year shown of the global mean temperature response from 4x*CO_2 *concentration step in CMIP5 models (grey) and SCMs (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, FAIR – pink, AR5-IR –green).*

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Table S9 shows the ECS values and the realized warming fraction (RWF) for the CMIP5 data and SCMs used to produce Figure 45. The RWF reveals that the SCMs used in this study generally warm faster than the more complex models in CMIP5.

Table S10 *CMIP5 and SCM model information with ECS and RWF*

Centre(s)	Model name	ESC (°C)	RWF (%) $\sqrt{2}$ ~~$LN(2)$~~ $x\,\frac{Average\ of\ the\ last\ 40\ years}{ECS}$
Beijing Climate Center (BCC) **China**	BCC-CSM1.1	2.8	58~~83.4~~
Canadian Centre for Climate Modelling and Analysis (CCCma) **Canada**	CanESM2	3.7	54~~77.0~~
National Center for Atmospheric Research **USA**	CCSM4	2.9	51
Centre National de Recherches Météorologiques, Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique (CNRM-CERFACS) **France**	CNRM-CM5~~-2~~	3.3	51~~69.7~~
Commonwealth Scientific and Industrial Research Organization/Queensland Climate Change Centre of Excellence **Australia**	CSIRO-Mk3-6-0	4.1	47
Institut Pierre Simon Laplace (IPSL) **France**	IPSL-CM5A-LR	4.1	49~~69.8~~
	IPSL-CM5A-MR	NA	--~~NA~~
	IPSL-CM5B-LR	2~~3~~.6	54~~72.9~~

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Institute of Atmospheric Physics, Chinese Academy of Sciences (LASG-CESS) **China**	FGOALS-g2	NA	--~~NA~~
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology (MIROC) **Japan**	MIROC-ESM	4.7	48~~65.1~~
	MIROC5	2.7	49~~68.6~~
Max Planck Institute for Meteorology (MPI-M) **Germany**	MPI-ESM-MR	NA	--~~NA~~
	MPI-ESM-P	3.5	51~~71.7~~
Meteorological Research Institute **Japan**	MRI-CGCM3	2.6	55
Norwegian Meteorological Institute **Norway**	NorESM1-M	2.8	48
NASA/GISS (Goddard Institute for Space Studies; NASA-GISS) **USA**	GISS-E2-H	2.3	49~~70.2~~
	GISS-E2-R	2.1	44~~62.3~~
Geophysical Fluid Dynamics Laboratory (NCAR; NSF-DOE-NCAR) **USA**	GFDL-CM3	4.0	52~~70.5~~
	GFDL-ESM2G	2.4	57~~82.9~~
	GFDL-ESM2M	2.4	65
Raper et al.,~~.~~ 1996; Wigley and Raper 2002; Smith and Bond 2014	MAGICC 5.3 BC-OC	3.0*	64~~82.0~~
Meinshausen et al.,~~.~~ 2011	MAGICC 6.0	3.0*	53~~83.8~~
Hartin et al.,~~.~~ 2015	Hector v2.0	3.0*	63~~90.3~~

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Hartin et al.,~~.~~ 2016			
Millar et al.,~~.~~ 2017	FAIR	2.75	61~~86.2~~
Myhre et al.,~~.~~ 2013	AR5-IR	2.7	88~~66.8~~

*Unless otherwise noted.

Note: NA denotes models that have not reported an ESC value from Table 9.5 in IPCC AR5(Flato et al., 2013).

S11 Simple Sensitivity Tests in SCMs

Here we discuss the SCM responses under a range of climate sensitivity and ocean diffusivity values.

S11~~Note: NA denotes models that have not reported an ESC value from Table 9.5 in IPCC AR5(Flato et al. 2013).~~

S10.1 Changing Equilibrium Climate Sensitivity Values in SCMs with Comparison to CMIP5

We changed the ECS values in the SCMs to illustrate the effects of parameter selection on the model responses. We reproduce Figure 4Here we reproduce Figure 5 from the main paper using different ECS values in Hector v2.0, MAGCC 5.3, and MAGIC 6.0. We run each of these SCMs with a climate sensitivity values of 2.1°C, the same as GISS-E2-R, and 4.7°C, the same as MIROC-ESM. These two model values were selected because they represent the largest range of climate sensitivity values in the model data used here.

shows the global mean temperature response from 4xCO_2 concentration step in CMIP5 models and SCMs. The SCMs were run with two different ECS values. a shows the SCM response with an ECS value of 2.1°C and b shows the SCM responses with an ECS value of 4.7°C. We found that spanning the range of complex model ECS values still resulted in stronger SCM responses, which supports the conclusion in our main paper that the SCMs have a faster warming rate under strong forcing regimes compared to more complex models.

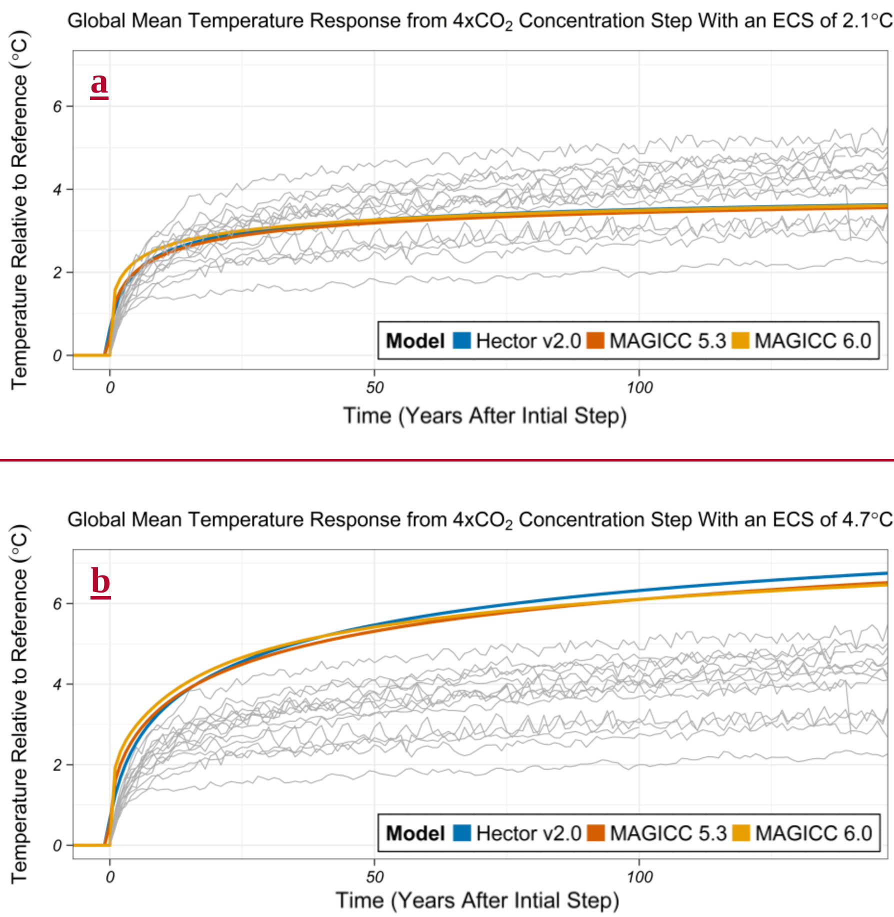

Figure S25 *Global mean temperature response from 4xCO2 concentration step in CMIP5 models and SCMs, as in Figure 5, with the SCMs run with two different ECS values. Figure 22a shows the SCM response with an ECS value of 2.1°C, and Figure 22b shows the SCM responses with an ECS value of 4.7°C (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue)*

S11.2 Additional Sensitivity Experiment in SCMs Using MAGICC6.0 Parameters

The aim of this paper is not to validate any individual simple climate model (SCM), nor the range of parameters used in the SCMs, which are also explored in the literature cited in our manuscript. Rather, we are evaluating the fundamental behavior of the simple models. However, understanding the uncertainty associated with our results is important.

In S11.1 we conducted a simple sensitivity test for the 4xCO_2 concentration step experiment by changing the climate sensitivity values in the three comprehensive SCMs used in this paper. Below, we have added some additional tests by exploring a range of climate sensitivity values and ocean diffusivity values in MAGICC 6.0 under a unit pulse of CO_2 emissions and a unit pulse of CO_2 concentration.

We selected climate sensitivity and ocean diffusivity values from the parameter ranges presented in Table 1B in Meinshausen et al. (2011). The values are the native MAGICC 6.0 parameters required to emulate complex models used in CMIP3 using three calibrated parameters (climate sensitivity, ocean diffusivity, and land/ocean warming). We provided the climate sensitivity and ocean diffusivity value ranges we explored in Table 11 below.

Table S11 MAGICC 6.0 parameter values from Meinshausen et al., 2011 Table 1B for sensitivity tests

Scenario	Climate sensitivity (K)	Ocean diffusivity ($cm^2 s^{-1}$)
Base Case	3.0	1.1
High Ocean diffusivity	3.0	3.74
Low Ocean diffusivity	3.0	0.50
High Climate sensitivity	6.03	1.1
Low Climate sensitivity	1.94	1.1

Figure 26 shows the global mean temperature response exploring the range of ocean diffusivity (Kz) (a) and global mean temperature response exploring the range of climate sensitivity (CS) (b) under a CO_2 emissions perturbation. Figure 27 shows the same results for under a CO_2 concentration pulse. Both figures illustrate that climate sensitivity has the greatest impact on the responses and in our manuscript, we accounted for this and used similar climate sensitivity values in SCMs where possible, unless otherwise noted in the supplemental figures.

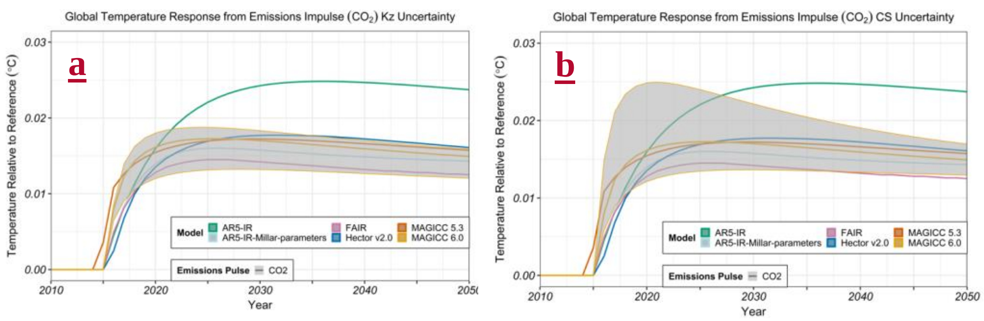

Figure 26 *Global mean temperature response exploring the range of ocean diffusivity (Kz) (a) and Global mean temperature response exploring the range of climate sensitivity (CS) (b) from a CO_2 emissions perturbation in SCMs. The grey shaded region in each figure shows the range in MAGICC 6.0 responses found using the Table S11 parameters. We note that the range of responses exploring CS (b) are normalized to account for the different climate conditions under difference CS values. (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, AR5-IR – green, FAIR – pink, AR5-IR-Millar-parameters –light blue)*

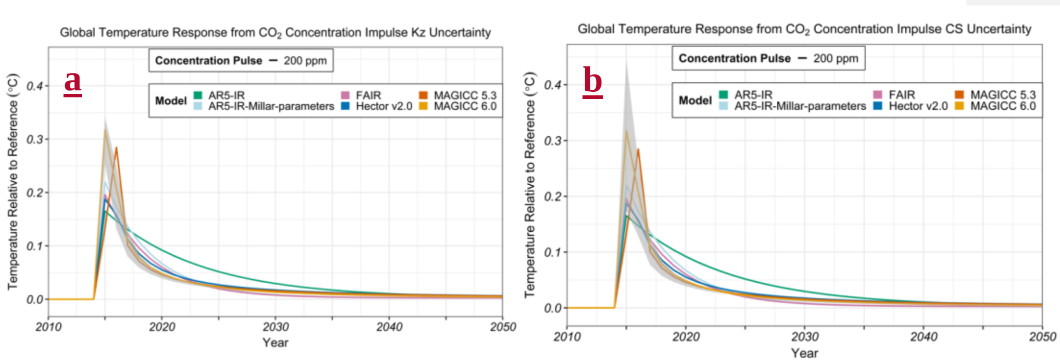

Figure 27 *Temperature response exploring the range of climate sensitivity (CS) (b) from a CO_2 concentration pulse in SCMs (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, AR5-IR – green, FAIR –pink, AR5-IR-Millar-parameters –light blue). The grey shaded region in each figure shows the range in MAGICC 6.0 responses found using the Table R2 parameters. We note that the range of responses exploring CS (b) are normalized to account for the different climate conditions difference CS values.*

We acknowledge, however, that vertical ocean diffusivity has a large impact on ocean heat uptake and we do note that this parameter selection also impacts the responses in the SCMs, particular under a CO_2 emissions pulse (Meinshausen et al., 2011). However, the SCMs we compare in our paper either do not have the same definitions of vertical ocean diffusivity, as is the case for the comprehensive SCMs, or ocean diffusivity is not directly represented in the models, as is the case for idealized SCMs. For our purposes, therefore, we kept the ocean diffusivity values at their default values within the comprehensive SCMs.

For completeness, we also acknowledge that Meinshausen et al. (2011) spanned ranges of land/ocean warming contrast (RLO) in the three-parameter calibration described in Table 1B of their manuscript. And again, the SCMs either use the same values of RLO, as is the case for both versions of MAGICC, or this parameter is not represented in the idealized models. In fact, from our work using impulse response test to characterize SCMs, we concluded that SCMs without differential warming do not correctly capture the response pattern to BC perturbations.

S12 Comparison to Previous Impulse Responses Work by Joos et al. (2013)

We conducted the same perturbation experiment done by Joos et al. (2013) with our three comprehensive SCMs and two stylized SCMs, however, we do not conduct this against a constant CO_2 concentration background. Instead, we use the RCP 4.5 scenario and add a 100GtC CO_2 pulse in 2015. The versions used in each study differ slightly. Joos et al. used MAGICC model version 6.3 run in 171 different parameter settings that emulate 19 AOGCMs and 9 coupled climate-carbon cycle models. MAGICC 6.0 used in this study was set at the default setting using the AOGCM multi-model mean.

Table S12

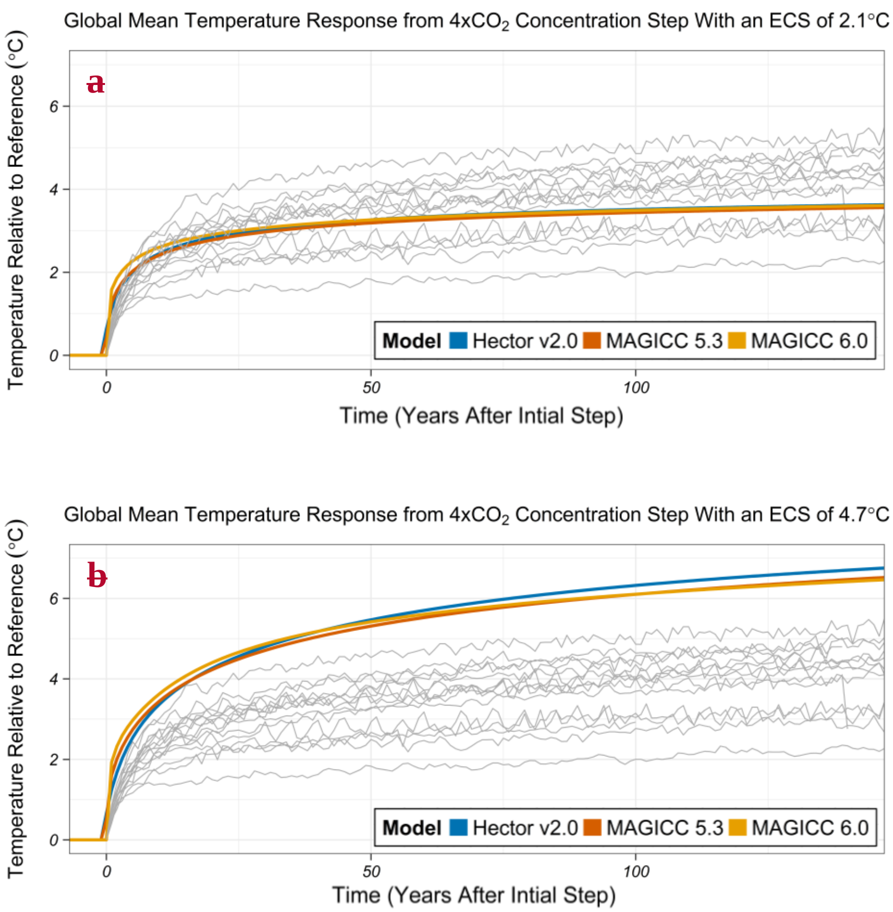

Figure S22 *Global mean temperature response from 4xCO2 concentration step in CMIP5 models and SCMs, as in Fig. 5, with the SCMs run with two different ECS values. Fig. 22a shows the SCM response with an ECS value of 2.1°C, and Fig. 22b shows the SCM responses with an ECS value of 4.7°C (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue)*

S11 Comparison to Previous Impulse Reponses Work by Joos *et al.*(Joos et al. 2013)

We conducted the same perturbation experiment done by Joos et al. (Joos et al. 2013) with our three comprehensive SCMs and two stylized SCMs, however, we do not conduct this against a constant CO_2 concentration background. Instead, we use the RCP 4.5 scenario and add a 100GtC CO_2 pulse in 2015. It is useful to note that MAGICC 6.0 was used both in this study and by Joos *et al*. The versions used in each study differ slightly. Joos *et al.* used MAGICC model version 6.3 run in 171 different parameter settings that emulate 19 AOGCMs and 9 coupled climate-carbon cycle models. MAGICC 6.0 used in this study was set at the default setting using the AOGCM multi-model mean.

Table S10 shows the time-integrated airborne fraction at chosen time horizons from the 100 GtC pulse of CO_2 emissions. The Table S10 results are graphically represented in Figure S28SI. Fig. 23. These results are largely discussed in the main paper.

Table S12 Time-integrated Airborne Fraction from a 100 GtC CO_2 Emissions Impulse in SCMs Compared to Results from Table 4 in Joos et al. (2013)

~~Time-integrated Airborne Fraction from a 100 GtC CO_2 Emissions Impulse in SCMs Compared to Results from Table 4 in Joos *et al.* (Joos et al. 2013)~~

Time Horizon	20 yr	50 yr	100 yr
NCAR CSM1.4	13.8	27.8	46.6
HadGEM2-ES	14.7	30.9	53.3
MPI-ESM	14.5	29.2	48.8
Bern3D-LPJ (reference)	15.4	34.3	61.9
Bern3D-LPJ ensemble	15.1 (14.0-16.0)	32.7 (28.9-36.0)	57.6 (48.9-65.6)
Bern2.5D-LPJ	13.9	29.7	51.1
CLIMBER2-LPJ	13.0	26.8	49.2
DCESS	14.6	31.8	56.3
GENIE ensemble	13.6 (10.9-17.6)	28.9 (21.7-41.4)	50.5 (38.3-77.9)
LOVECLIM	13.5	27.9	45.3
MESMO	15.1	33.6	61.1
UVic2.9	13.7	29.5	53.0
ACC2	13.7	27.9	46.5
Bern-SAR	14.0	29.0	48.9
TOTEM2	16.9	38.3	66.6
MAGICC 6.0 ensemble	14.0 (12.0-16.1)	29.6 (23.6-35.7)	51.8 (40.0-64.2)
Multi-model mean	14.3 ± 1.8	30.2 ± 5.7	52.4 ± 11.3
Hector v2.0	16.2	34.0	58.3
MAGICC 5.3	16.0	33.4	58.3
MAGICC 6.0	15.3	32.2	57.9
AR5-IR	15.0	31.0	53.1
FAIR	14.6	32.6	61.6

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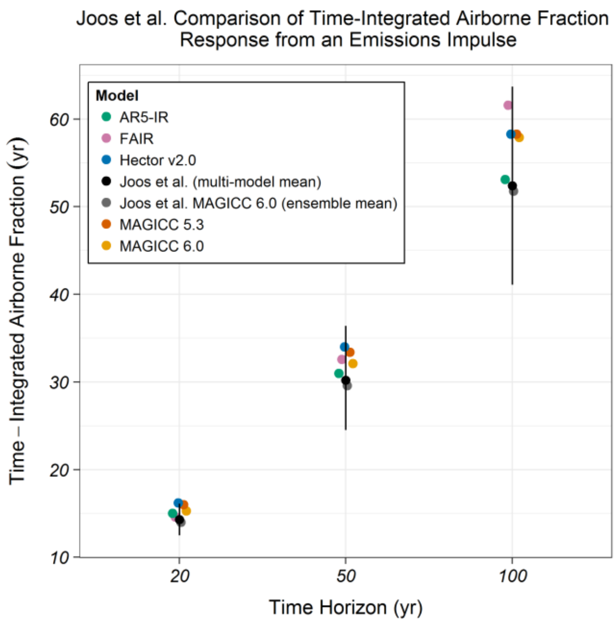

Figure S28 *Time-integrated airborne fraction from a 100GtC CO_2 emissions impulse in SCMs compared to Joos et al. This is not a direct comparison because we did not perform this experiment with a constant CO_2 concentration background, as done by Joos et al. The colored points represent the time-integrated airborne fraction in the SCMs used in this study, following Joos et al., and the Joos et al. MAGICC 6.0 ensemble mean. The black point is the Joos et al. multi-model mean and the vertical black line represents the range of the Joos et al. model results. (Joos et al. MAGICC 6.0 ensemble mean –grey, MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue, AR5-IR – green, FAIR –pink).*

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We also indirectly compare the temperature response of the comprehensive SCMs and more complex models in Joos et al. MAGICC 6.0 was used both here and by Joos et al., and we find similar responses with ≤ 1 °C yr difference from Joos et al. at each reported period. Though the other two comprehensive SCMs were not used by Joos et al., their similar responses to our MAGICC 6.0 allow us to make a larger conclusion, as done in the main paper. Using this logic, we are able to validate our SCM responses from a finite pulse., without conducting this experiment in ESMs or EMICs, directly. We find that the comprehensive SCM responses are generally less varied, close to the Joos et al. ensemble mean 20 years after the pulse, and below most Joos et al. model responses 50 and 100 years after the pulse (see Figure S29S24).

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Table S13 Time-integrated temperature response from a 100 GtC CO_2 Emissions Impulse in SCMs Compared to Results from Table 7 in Joos et al. (2013).

Time Horizon	**20 yr**	**50 yr**	**100 yr**
NCAR CSM1.4	2.53	7.36	10.6
HadGEM2-ES	4.24	12.4	30.3
MPI-ESM	3.83	8.84	19.1
Bern3D-LPJ (reference)	4.11	12.1	24.5
Bern3D-LPJ ensemble	3.20 (2.1-4.6)	8.61 (5.1-13.5)	17.3 (9.5-29.3)
Bern2.5D-LPJ	3.15	8.40	17.1
CLIMBER2-LPJ	3.05	7.96	16.5
DCESS	3.38	9.96	20.6
GENIE ensemble	3.77	10.54	21.6
LOVECLIM	0.22	3.46	7.83
MESMO	4.41	12.5	26.0
UVic2.9	3.40	9.17	18.5
ACC2	3.99	10.55	20.0
Bern-SAR	n/a	n/a	n/a
TOTEM2	n/a	n/a	n/a
MAGICC 6.0 ensemble	3.64 (2.7-4.7)	8.96 (6.6-12.7)	17.2 (12-26)
Multi-model mean	3.29 ± 2.03	9.13 ± 4.45	18.7 ± 11.1
Hector v2.0	3.05	8.20	15.54
MAGICC 5.3	3.13	8.19	15.73
MAGICC 6.0	3.39	8.28	15.54

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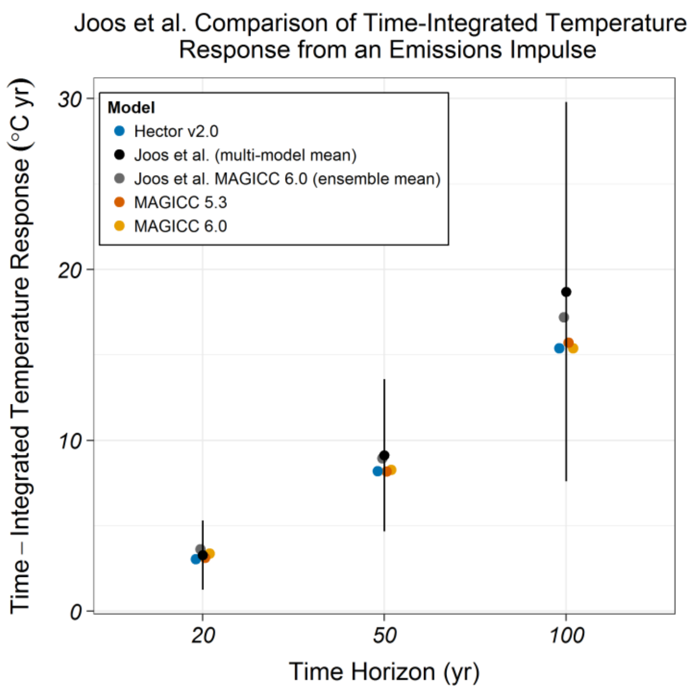


Figure S29 *Time-integrated temperature response from a 100GtC CO_2 emissions impulse in SCMs compared to Joos et al. This is not a direct comparison because we did not perform this experiment with a constant CO_2 concentration background, as done by Joos et al. The colored points represent the time-integrated temperature response in the SCMs used in this study, following Joos et al., and the Joos et al. MAGICC 6.0 ensemble mean. The black point is the Joos et al. multi-model mean and the vertical black line represents the range of the Joos et al. model results. (Joos et al. MAGICC 6.0 ensemble mean –grey, MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue).*

We compare the comprehensive SCM responses from the 100GtC CO_2 pulse to our earlier experiment using a ~10GtC CO_2 pulse. We find that the relative behavior of the comprehensive SCMs in the 100 GtC CO_2 impulse is similar to the response pattern from the smaller pulse experiment (see Figure 3a and Figure S29). The MAGICC 6.0 temperature response pattern is consistent with our prior experiments, where we see an initially stronger response (10 years following the perturbation) compared to the other comprehensive SCMs. Due to the initial oscillatory behavior in complex model responses (see Figure 2a in Joos et al. (2013)), it is difficult to compare SCM responses to complex models on these short time scale.

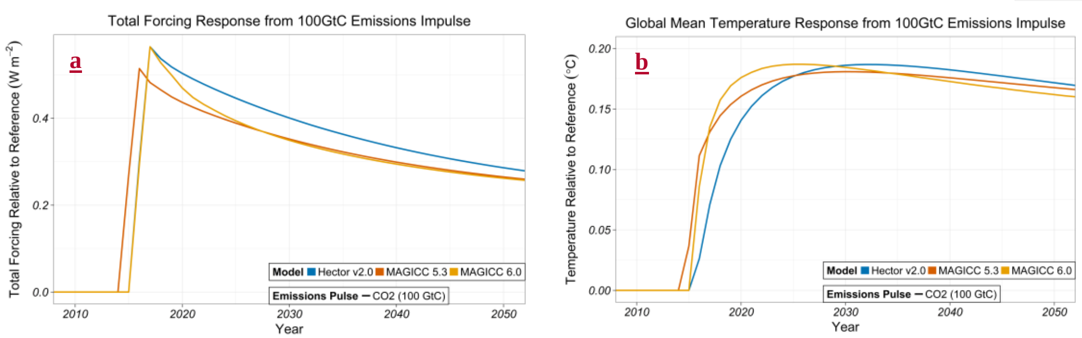


Figure S30 *Total forcing response (a) and global mean temperature response (b) from a 100GtC CO2 emissions impulse in the SCMs (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue).*

S13 Investigating Temperature Response from BC Step Experiment

We investigate SCM responses to a black carbon (BC) emissions step by quadrupling (4x) the values in 2015. We choose two of the SCMs, Hector v2.0 and MAGICC 5.3, as examples and compare the temperature response to Figure 1 in Sand et al. (2016). Sand et al. finds that after applying a 25x BC emissions step to NorESM1-M, a complex climate model, the temperature response levels off after less than 10 years. We find that temperature in both of these SCMs continue to increase over a century time-scale after the BC perturbation. The SCMs, therefore, fail to capture the temporal response to BC as seen in Sand et al. (2016), also seen in Yang et al. (2019).

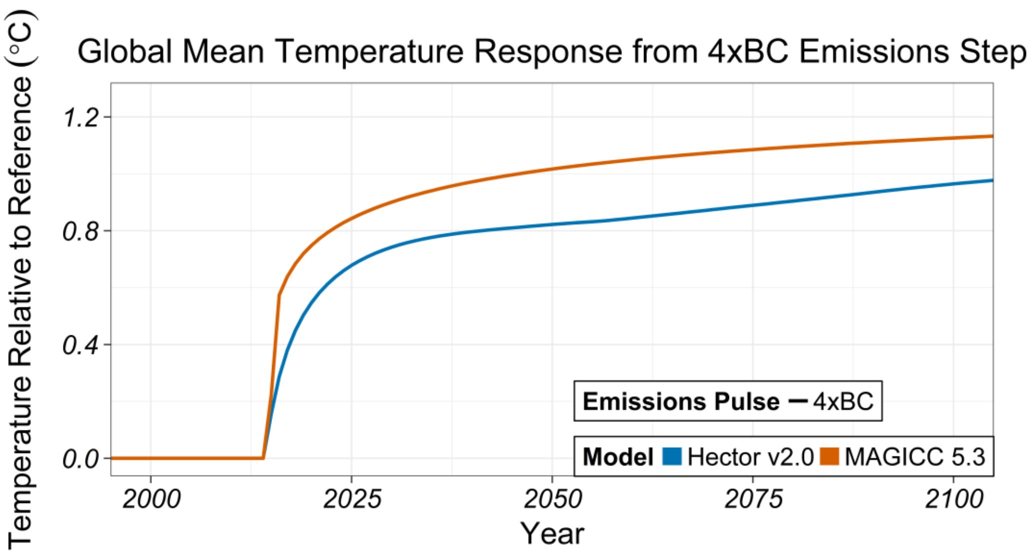
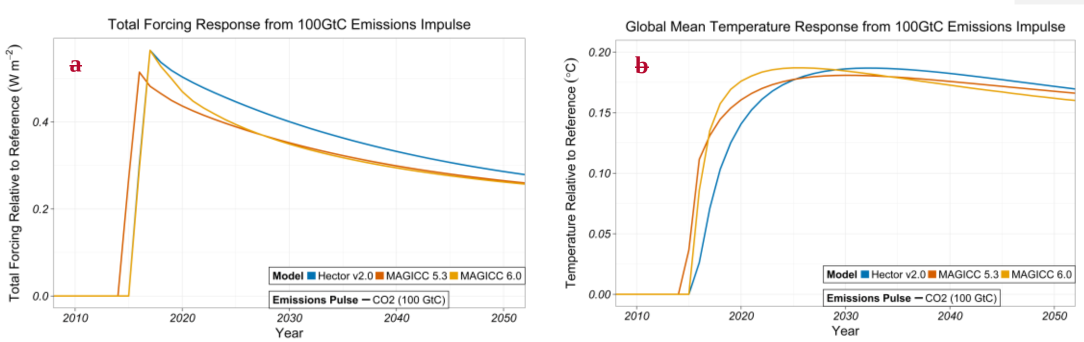


Figure S31 *Global mean temperature response from a 4xBC emissions step in the SCMs (MAGICC 5.3 BC-OC – red, Hector v2.0 – blue).*

We compare the comprehensive SCM responses from the 100GtC CO_2 pulse to our earlier experiment using a ~10GtC CO_2 pulse. We find that the relative behavior of the comprehensive SCMs in the 100 GtC CO_2 impulse is similar to the response pattern from the smaller pulse experiment (see Figure 3a and Figure S25). The MAGICC 6.0 temperature response pattern is consistent with our prior experiments, where we see an initially stronger response (10 years following the perturbation) compared to the other comprehensive SCMs. Due to the initial oscillatory behavior in complex model responses (see Figure 2a in Joos *et al.*(Joos et al. 2013)), it is difficult to compare SCM responses to complex models on these short time scale.



~~**Figure S25** *Total forcing response (a) and global mean temperature response (b) from a 100GtC CO2 emissions impulse in the SCMs (MAGICC 6.0 – yellow, MAGICC 5.3 BC-OC – red, Hector v2.0 – blue).*~~

S12 Investigating Temperature Response from BC Step Experiment

We investigate SCM responses to a black carbon (BC) emissions step by quadrupling (4x) the values in 2015. We choose two of the SCMs, Hector v2.0 and MAGICC 5.3, as examples and compare the temperature response to Figure 1 in Sand *et al* (Sand et al. 2016). Sand *et al.* finds that after applying a 25x BC emissions step to NorESM1-M, a complex climate model, the temperature response levels off after it reaches 1.2K after less than 10 years. Sand *et al.* applies a large BC step to increase the signal in the complex model, while we apply a smaller step in the SCMs. We find that the SCM responses to a BC emissions step continue to increase 10 years after the perturbation, suggesting that the SCMs fail to capture aerosol dynamics.

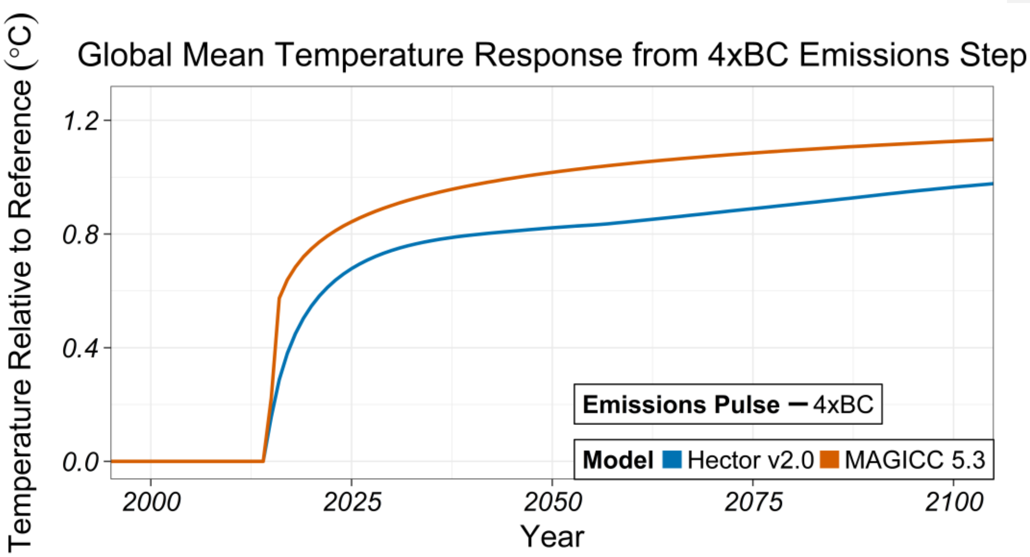


Figure S26 *Global mean temperature response from a 4xBC emissions step in the SCMs (MAGICC 5.3 BC-OC – red, Hector v2.0 – blue).*

S13

S14 Summary of SCM Performance in Table 1

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Here we describe the choice of reportingWe provide a summary of SCM performance for each of our recommended unit tests in Table 1 in the main paper. We justifiedHere, we describe the performance scale used in Table 1.

Using results from Joos *et al.* (Joos et al. 2013), we found that the MAGICC 6.0 temperature response to a 100GtC CO_2 emissions impulse was similar to more complex models. In the main text, therefore, we use of the integratedMAGICC 6.0 as a reference to understand the other comprehensive SCM responses. We report that the comprehensive SCM carbon cycle representations, including from MAGICC 5.3 and Hector v2.0, generally capture more complex model responses. For unit tests where we cannot directly compare the responses to complex model, therefore, we use the comprehensive SCM average.

We developed the performance scale in Table 1 generally using the time-integrated temperature response percent difference in the main paper, and report additional from the comprehensive SCM average. We set the scale based on the range in percent differences in S9. In Table 1, we report the integrated response percentfound in our analysis: • : 0-10% difference for each of the experiments conducted in the SCMs at selected time horizons. We chose to report the time horizons for each experiment by taking into consideration the atmospheric lifetime of the species and the ability to compare the experiments. , •• : 10-20% difference, and ••• : 20-30% difference from the comprehensive SCM average (see S9).

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For example, towe assign the comprehensive SCM responses to a CO_2 concentration impulse a three (•••) because the responses are within 10% of the comprehensive SCM average. The idealized SCMs, FAIR v1.0 and AR5-IR, have greater differences and are given a two (••) and a one (•), respectively.

Under the 4xCO_2 concentration step experiment, we can compare the experiments exploring responses to CO2SCM response to more complex models from CMIP5. We assign MAGICC 6.0 a three (•••) because it appears to respond more reasonably under stronger forcing conditions than the other SCMs. We assign Hector v2.0, MAGICC 5.3, and FAIR a two (••) because these SCMs have initially quicker responses to an abrupt 4xCO_2 concentration increase compared to the ESMs. We assign AR5-IR a one (•) because it has a slower response to an abrupt 4xCO_2 concentration increase and is insensitive to changing background concentrations.

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For CH_4 emissions impulses, we use the difference from the comprehensive SCM average to rate the responses. Unlike the 100GtC CO_2 and 4xCO_2 step experiments, we cannot compare the SCM responses to more complex models, therefore, we are more lenient in our performance assignment against the comprehensive SCM average. CH_4 is a well-mixed GHG and, therefore, we expect that the climate system response to CH_4 concentration perturbations, we report the responses at 100 years after the pulse. For CH4 and will be similar to that for CO_2. However, it would be useful to evaluate in more complex models if the simple representation of chemistry in the comprehensive SCMs adequately represents the time evolution of CH_4 concentrations in response to a change in emissions.

Finally, we assign ratings to the SCM responses to aerosols. We do not explicitly conduct aerosol experiments other than BC, we report at a shorter time horizon of 20 years after the pulse. because the responses of the SCMs to other aerosols will be similar to their response to BC. We do not have a definitive reference for the time-dependent response to aerosol forcing perturbations. Instead, we rate the SCMs using the difference from the average of both MAGICC models, which both differentiate aerosol forcing between land and ocean, which results in a faster overall climate response to aerosols as compared to greenhouse gases (Shindell 2014). In the case of BC, we note that all SCM response ratings should be reduced from the values shown because they do not accurately represent the temporal response to a BC step found in an ESM (see S12). A more definitive evaluation of climate system responses to aerosol perturbations would be useful. This would require additional GCM simulations to step emission changes for various aerosol species and/or forcing mechanisms.

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~~S14~~S15 Supplementary Data

Other supplementary materials for this manuscript can be found at https://github.com/akschw04/Fundamental-Impulse-Tests-in-SCMs-Datasets and include the following:

Dataset S1 (separate file)

Simple climate model responses from 4xBC emissions step.

Dataset S2 (separate file)

Simple climate model responses from 4xCO_2 concentration step with 2.3 ocean diffusion and an ECS = 3 °C.

Dataset S3 (separate file)

Simple climate model responses from a 100PgC CO_2 emissions impulse experiment.

Dataset S4 (separate file)

Simple climate model responses from a CH_4 emissions impulse experiment.

Dataset S5 (separate file)

Simple climate model responses from a BC emissions impulse experiment.

Dataset S6 (separate file)

Simple climate model responses from CO_2 concentration impulse experiment.

Dataset S7 (separate file)

Simple climate model responses from CO_2 emissions impulse experiment.

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Dataset S8 (separate file)

AR5-IR code to produce responses to BC emissions impulse.

Dataset S9 (separate file)

AR5-IR code to produce responses to CH_4 emissions impulse.

Dataset S10 (separate file)

AR5-IR code to produce responses to CO_2 emissions impulse.

Dataset S11 (separate file)

AR5-IR code to produce responses to 100PgC CO_2 emissions impulse for comparison to Joos *et al.* (2013)

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Dataset S12 (separate file)

AR5-IR code to produce responses to CO_2 concentration step.

Dataset S13 (separate file)

FAIR CO_2 concentration impulse experiment input file.

Dataset S14 (separate file)

FAIR 4xCO_2 concentration step experiment input file.

Dataset S15 (separate file)

FAIR CO_2 emissions impulse experiment input file.

Dataset S16 (separate file)

FAIR 100Pg CO_2 emissions impulse experiment input file.

Dataset S17 (separate file)

FAIR CO_2 emissions impulse experiment reference input file.

Dataset S18 (separate file)

Hector v2.0 CO_2 concentration impulse experiment input file.

Dataset S19 (separate file)

Hector v2.0 CO_2 concentration impulse experiment reference input file.

Dataset S20 (separate file)

Hector v2.0 4xCO_2 concentration step experiment reference input file.

Dataset S21 (separate file)

Hector v2.0 4xCO_2 concentration step experiment input file.

Dataset S22 (separate file)

Hector v2.0 BC emissions impulse experiment input file.

Dataset S23 (separate file)

Hector v2.0 BC emissions step experiment input file.

Dataset S24 (separate file)

Hector v2.0 CH_4 emissions impulse experiment input file.

Dataset S25 (separate file)

Hector v2.0 CO_2 emissions impulse experiment input file.

Dataset S26 (separate file)

Hector v2.0 100Pg CO_2 emissions impulse experiment input file.

Dataset S27 (separate file)

Hector v2.0 emissions impulse experiment reference input file.

Dataset S28 (separate file)

Hector v2.0 emissions step experiment reference input file.

Dataset S29 (separate file)

MAGICC5.3 CO_2 concentration impulse experiment reference input file.

Dataset S30 (separate file)

MAGICC5.3 CO_2 concentration impulse experiment input file.

Dataset S31 (separate file)

MAGICC5.3 4xCO_2 concentration step experiment input file.

Dataset S32 (separate file)

MAGICC5.3 4xCO_2 concentration step experiment reference input file.

Dataset S33 (separate file)

MAGICC5.3 BC emissions impulse experiment input file.

Dataset S34 (separate file)

MAGICC5.3 BC emissions step experiment input file.

Dataset S35 (separate file)

MAGICC5.3 CH_4 emissions impulse experiment input file.

Dataset S36 (separate file)

MAGICC5.3 1% CO_2 emissions impulse experiment in 2010 input file.

Dataset S37 (separate file)

MAGICC5.3 1.01% CO_2 emissions impulse experiment in 2010 input file.

Dataset S38 (separate file)

MAGICC5.3 5% CO_2 emissions impulse experiment in 2010 input file.

Dataset S39 (separate file)

MAGICC5.3 10% CO_2 emissions impulse experiment in 2010 input file.

Dataset S40 (separate file)

MAGICC5.3 50% CO_2 emissions impulse experiment in 2010 input file.

Dataset S41 (separate file)

MAGICC5.3 100% CO_2 emissions impulse experiment in 2010 input file.

Dataset S42 (separate file)

MAGICC5.3 100% CO_2 emissions impulse experiment in 2015 input file.

Dataset S43 (separate file)

MAGICC5.3 100% CO_2 emissions impulse experiment in 2020 input file.

Dataset S44 (separate file)

MAGICC5.3 100% CO_2 emissions impulse experiment in 2030 input file.

Dataset S45 (separate file)

MAGICC5.3 100% CO_2 emissions impulse experiment in 2040 input file.

Dataset S46 (separate file)

MAGICC5.3 100% CO_2 emissions impulse experiment in 2050 input file.

Dataset S47 (separate file)

MAGICC5.3 100% CO_2 emissions impulse experiment in 2060 input file.

Dataset S48 (separate file)

MAGICC5.3 100% CO_2 emissions impulse experiment in 2070 input file.

Dataset S49 (separate file)

MAGICC5.3 100PgC CO_2 emissions impulse experiment in 2015 input file.

Dataset S50 (separate file)

MAGICC5.3 CO_2 emissions impulse experiment reference input file.

Dataset S51 (separate file)

MAGICC5.3 CO_2 emissions step experiment reference input file.

Dataset S52 (separate file)

MAGICC56.0 4xCO_2 concentration impulse experiment input file.

Dataset S53 (separate file)

MAGICC56.0 4xCO_2 concentration impulse experiment reference input file.

Dataset S54 (separate file)

MAGICC56.0 4xCO_2 concentration step experiment input file.

Dataset S55 (separate file)

MAGICC56.0 4xCO_2 concentration step experiment reference input file.

Dataset S56 (separate file)

MAGICC6.0 BC emissions impulse experiment input file.

Dataset S57 (separate file)

MAGICC6.0 CH_4 emissions impulse experiment input file.

Dataset S58 (separate file)

MAGICC6.0 100% CO_2 emissions impulse experiment input file.

Dataset S59 (separate file)

MAGICC6.0 100PgC CO_2 emissions impulse experiment input file.

Dataset S60 (separate file)

MAGICC6.0 emissions impulse experiment reference input file.

Dataset S61 (separate file)

MAGICC 6.0 MAGCFG_USER parameters.

Dataset S62 (separate file)

FAIRv1.0 model with general parameters.

Dataset S63 (separate file)

AR5-IR general parameters.

Dataset S64 (separate file)

Hector general parameters.

Dataset S65 (separate file)

MAGICC5.3 maggas_c parameters.

Dataset S66 (separate file)

MAGICC5.3 magice_c parameters.

Dataset S67 (separate file)

MAGICC5.3 magmod_c parameters.

Dataset S68 (separate file)

MAGICC5.3 magrun_c parameters.

Dataset S69 (separate file)

MAGICC5.3 maguser_c parameters.

Dataset S70 (separate file)

MAGICC5.3 magxtra_c parameters.

S16~~S15~~ References

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