
Investigating Two Simple Climate Models Using Impulse Response Tests

Presented by

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Abstract

Reduced-form models, or simple climate models (SCMs), are a class of model used to understand the effects of anthropogenic perturbations on the climate system. SCMs are easy to use and computationally inexpensive, making them an ideal model for a variety of analyses and important for decision-making-related and scientific research. In this study we compare two SCMs, Hector v1.1 and MAGICC 5.3, to diagnose model behavior and understand the fundamental responses of the carbon cycle and climate system. Hector v1.1 is a new reduced form climate carbon-cycle model, while MAGICC 5.3 is a well-known SCM, commonly used in the literature. Previous studies have noted the importance of investigating model behavior with the ultimate goal of understanding important indicators, such as the transient climate response (TCR) or changes in the carbon cycle. In this study, we discovered that Hector v1.1 responds differently from MAGICC 5.3 to stylized perturbations of three different chemical species: carbon dioxide (CO_2), methane (CH_4), and black carbon (BC). Some of these differences require further investigation, such as the observed negative temperature response to a BC perturbation in Hector v1.1. Other differences were expected, and included non-linearities within Hector v1.1 likely resulting from non-linear ocean carbon chemistry. Through model evaluation and comparison, fundamental perturbation tests remain a valuable tool to the modeling community in diagnosing model behavior and understanding fundamental model responses to anthropogenic perturbations.

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List of Symbols

- A. ESMs: Earth System Models
- B. SCMs: Simple Climate Models
- C. IAMs: Integrated Assessment Models
- D. IPCC AR5: Intergovernmental Panel on Climate Change Fifth Assessment Report
- E. CO₂: Carbon Dioxide
- F. [X]: Concentration of X
- G. CMIP: Coupled Model Intercomparison Project (Phase 3,4,5)
- H. MAGICC 6: Model for the Assessment of Greenhouse Gas Induced Climate Change 6
(latest version)
- I. RCP 4.5: Representative Concentration Pathway 4.5
- J. TCR: Transient Climate Response
- K. ECS: Equilibrium Climate Sensitivity
- L. RWF: Realized Warming Fraction
- M. Hector v1.1: Hector Version 1.1
- N. MAGICC 5.3: Model for the Assessment of Greenhouse Gas Induced Climate Change 5.3
(used in this study)
- O. SLCF: Short-lived Climate Forcers
- P. CH₄: Methane

Q. BC: Black Carbon

R. IRF: Impulse Response Function

S. GMST: Global Mean Surface Temperature

T. RLO: Ratio of Land-Ocean Warming

U. HL: High Latitude

V. LL: Low Latitude

Chapter 1. Introduction

The models used to understand climate change vary in complexity and span a range from simple energy balance models to the most complex type of climate models, Earth System Models (ESMs). While ESMs run on supercomputers and can take several months to simulate 100 years, simple climate models (SCMs), also known as reduced-form models, can simulate the same period on a personal computer in less than a minute (Van Vuuren et al. 2011). SCMs have less detailed physical processes; however they include the most fundamental climate components, such as representation of the global carbon cycle. SCMs generally have the ability to: (1) calculate concentrations of greenhouse gases from given emissions, (2) calculate global mean radiative forcing from concentrations, (3) convert radiative forcing to global mean temperature, and (4) model the carbon cycle, an essential part of the climate system (Meinshausen et al. 2011; Tanaka et al. 2007; Hartin et al. 2015). Their ease of use and computationally efficient nature make them an ideal platform for a variety of applications including uncertainty analyses, complex climate model emulation, and climate mitigation scenarios within integrated assessment models (IAMs) (Hartin et al. 2015). Many studies utilize SCMs to understand uncertainties in the carbon cycle by emulating complex model results, or by investigating climate indicators.

The Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5; Stocker et al. 2013) and Friedlingstein et al. (2014) specifically note two major sources of uncertainty: (1) physical processes and feedbacks, and the resulting uncertainty in climate response for greenhouse gas concentrations and aerosol forcing in terms of the global-mean temperature response, and regional climate change; (2) carbon cycle processes and feedbacks,

with the associated uncertainty on the relationship between carbon dioxide (CO_2) emissions and concentration ($[\text{CO}_2]$). The investigation of climate and carbon-cycle spread using SCMs is highly cited in the literature (Joos and Bruno 1996; Schimel 1998; Joos et al. 1999; Knutti et al. 2008; Meinshausen et al. 2008; Van Vuuren et al. 2011; Friedlingstein et al. 2014). Knutti et al. (2008), for example, used two SCMs, Bern2.5CC and MAGICC6, to emulate complex models, perturb model parameters, and found that uncertainties from carbon cycle feedbacks are less important than uncertainties from future emissions and climate sensitivity.

SCMs are also commonly used to emulate complex model results to understand the behavior of anthropogenic perturbations, and to address model spread in the various model intercomparison projects (MIPs). For instance, Knutti et al. emulated Coupled Model Intercomparison Project Phase 4 (C⁴MIP) and Phase 3 (CMIP3) results in MAGICC and Bern2.5CC (2008). A newer publication from Knutti and Sedláček (2013) looked at CMIP5 (Phase 5) uncertainty ranges by comparing temperature results with CMIP3 results emulated in MAGICC 6 and found model spread resulting from the same uncertainties identified by Friedlingstein et al. (2014). Another study by Van Vuuren et al. (2011) concluded that in most cases the results from the IAMs and SCMs were similar to the more complex CMIP5 models. However, Van Vuuren et al. (2011) noted that differences in SCM results can have implication 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).

Similarly, SCMs are also used to investigate climate indicators, such as transient climate response (TCR). TCR is the measure of the climate response to a $1\% \text{ yr}^{-1}$ increase

in $[\text{CO}_2]$ until doubling of CO_2 relative to pre-industrial level. TCR is useful for understanding the climate response on shorter time scales, as $[\text{CO}_2]$ doubling takes place in 70 years, a time-frame relevant for policy decisions (Flato et al. 2013, Table 9.5; Millar et al. 2015). Used in combination with TCR the equilibrium climate sensitivity (ECS) can also be used to attribute the fraction of observed warming to anthropogenic influences (Allen et al. 2008). Millar et al. (2015) investigated TCR and ECS within a global climate-calibrated impulse-response model to show the implications of these values on future climate projections by specifically looking at the realized warming fraction (RWF). RWF (ECS/TCR) provides insight into anthropogenic influences on warming.

Though SCMs have many uses and advantageous features, our study framed is a more fundamental look into model behavior and the response of the climate system in two SCMs, Hector v1.1 and MAGICC 5.3. Our initial goals are to diagnose model behavior and understand carbon-cycle and climate responses to stylized perturbations, with the aim to emulate complex model results in the future. Hector is a new reduced form climate carbon-cycle model, while MAGICC 5.3 is a well-known SCM used for comparison. This initial study compares Hector v1.1 and MAGICC 5.3 by using impulse response methods of CO_2 and short-lived climate forcers (SLCF), such as methane (CH_4) and black carbon (BC), to investigate the carbon-cycle and climate responses of the models.

Recently, the National Academies released their preliminary Assessment of Approaches to Updating the Social Cost of Carbon: Phase 1 Report on a Near-Term Update, which emphasized using impulse tests to understand long-term responses (2016). In the report, the National Academies highlighted three features that would create a robust, common “module”

to represent the relationship between CO₂ emissions and global mean surface temperature change, its uncertainty, and its profile over time (National Academies of Sciences, Engineering, and Medicine 2016). These three recommendations are:

1. The module's behavior should be consistent with the best available scientific understanding of the relationship between emissions and temperature change, its pattern over time, and its uncertainty. Specifically, the module should be assessed on the basis of both its response to a pulse of emissions and its response to long-term forcing trajectories (specifically, trajectories designed to assess transient climate response and transient climate response to emissions, as well as high- and low-emissions baseline trajectories). Given the degree of assessment they face, including consistency with observational data, the IPCC-class Earth system models provide a reference for evaluating the central projections of a climate module.
2. The proposed module should strive for simplicity and transparency so that the central tendency and range of uncertainty in its behavior are readily understood, are reproducible, and are amenable to continuous improvement over time through the incorporation of evolving scientific evidence.
3. The possible implications of the choice of a common climate module for the assessment of impacts of other, non-CO₂ greenhouse gases should also be considered.

The report highlighted many of reasons SCMs play important roles in scientific research, citing many advantageous features also included in Hector v1.1. For example, Hector v1.1 is open source (transparent) and modular (amenable to improvements)—two

recommendations specifically made in the report. Our work using emission impulses of CO₂ and SLCF (CH₄ and BC) in Hector v1.1 and MAGICC 5.3 further addresses the first recommendation made by the National Academies.

Chapter 2. Methodology

We considered four major unit tests to understand the responses of two SCMs, Hector v1.1 and MAGICC 5.3. These tests are listed here:

1. Emissions impulse of CO₂ and CH₄ → testing the response of the carbon cycle or other feedbacks
2. Forcing impulse of CO₂ and BC → testing the climate part of the model
3. Double [CO₂] → testing the approach to equilibrium
4. Increase [CO₂] by 1% *yr*⁻¹ until doubling → testing transient climate sensitivity.

Theoretically, our analysis using impulses tests can be justified because impulse response functions (IRF) characterize the dynamics of a linear system (Ruelle 2009; Joos and Bruno 1996). Though climate models have many nonlinearities, even some non-linear systems can be approximated by IRF, given perturbations are small. The IRF concepts explained here can be simply represented as a Green's function, the mathematical basis for simple model development (Joos et al. 1999; Van Vuuren 2011; Millar et al. 2015). A Green's function is the response of the system to a unit impulse at $t=t'$ given by:

$$y(t) = \int_0^{\infty} G(t, t') f(t') dt' \quad (1)$$

where $G(t, t')$ is the response to some forcing function $f(t')$ (Boas 2006).

The emissions perturbations allow us to understand the carbon cycle response and feedbacks within the models. In both MAGICC 5.3 and Hector v1.1, by perturbing the

models with a pulse of emissions, we can observe the response of concentration, total radiative forcing, and global mean surface temperature (GMST). Therefore, we can understand model responses by observing carbon cycle feedbacks (e.g. terrestrial uptake), chemistry feedbacks (e.g. CH₄ lifetime), GMST response, and sea level rise.

Similarly, a forcing pulse allows us to understand a fundamental response of the models, but by pulsing CO₂ or BC forcing we can understand the climate response by removing complicating influences from carbon cycle feedbacks. For example, a BC pulse increases GMST, subsequently causing a slight increasing the [CO₂] through this secondary effect.

The emissions and forcing impulses were carried out by pulsing one year (e.g. in 2010) of the emissions or forcing values for a particular chemical species (BC, CO₂, CH₄) and obtaining the response. The response is obtained by subtracting the perturbation results from the reference, where we use the Representative Concentration Pathway (RCP) 4.5 values as reference (Stocker et al. 2013). For instance, the CO₂ mixing ratio response is obtained as follows:

$$[CO_2]_{response}(t) = [CO_2]_{perturbation}(t) - [CO_2]_{reference}(t) \quad (2)$$

Our final unit tests were conducted by fixing the [CO₂] path in an effort to describe the TCR of MAGICC 5.3. To evaluate the TCR, we increased the [CO₂] in a given year by 1% annually, until doubling or quadrupling was reached. This method follows the formal definition of TCR from Chapter 9.7 of the IPCC AR5 (Stocker et al. 2013). The TCR and approach to equilibrium of Hector v1.1 were not investigated in this study because of the loss

of the ability to fix $[\text{CO}_2]$. The same procedure will be carried out in Hector v1.1 after code fixes are applied and the functionality is restored.

The TCR experiment was carried out using the two SCMs because perturbation experiments are computationally expensive and difficult to run in CMIP5 models, though a sample of 32 CMIP5 did conduct the stylized TCR experiment (Taylor et al 2012). By investigating the TCR within the two SCMs, we can compare these results to those within CMIP5 in the future. Similarly, the model approach to equilibrium can be explored by instantaneously doubling the $[\text{CO}_2]$ in a given year (e.g. 2010). The CMIP5 experiments also conducted a similar experiment (step function), where after CO_2 doubling, the abundance is held fixed. Step functions were also explored within MAGICC 5.3, but because the comparison cannot be made to Hector v1.1 at this time, the results are not included in this initial study.

Below is a summary of the runs conducted, and the associated figures throughout this study:

Table 1: Model Runs

Chemical Species	Perturbation Type	MAGICC 5.3 Figures	Hector v1.1 Figures
CO_2 Emissions	1%, 5%, 10%, 50%, 100%	1,2,3,11,12,13,14	6,??,7,8,10,12,13,14
CH_4 Emissions	100%	2,3,4,13,14,15	7,8,13,14,15
BC Forcing	100%	2,3,9,13,14,15	7,8,13,14,15
CO_2 Mixing Ratio	$1\% \text{ yr}^{-1}$, 100%	5	N/A

Chapter 3. Results

3.1 Impulse Response Tests: MAGICC 5.3

Utilizing MAGICC 5.3 as our baseline, the initial runs included pulses of CO₂, CH₄, and BC emissions of various sizes (1%, 5%, 10%, 50%, or 100% increase) in a given year. Figure 1 was created by taking the impulse response and normalizing the response to the pulse size, whether it is 1% (0.0881 Pg C for CO₂) or 100% (8.8065 Pg C for CO₂). Through this analysis it was determined the GMST response to emission perturbations in MAGICC 5.3 is linear (the lines are collinear; Figure 1). For example, a 1% (red) perturbation in 2010 responded no differently than a 50% (purple) or 100% (green) perturbation in 2010.

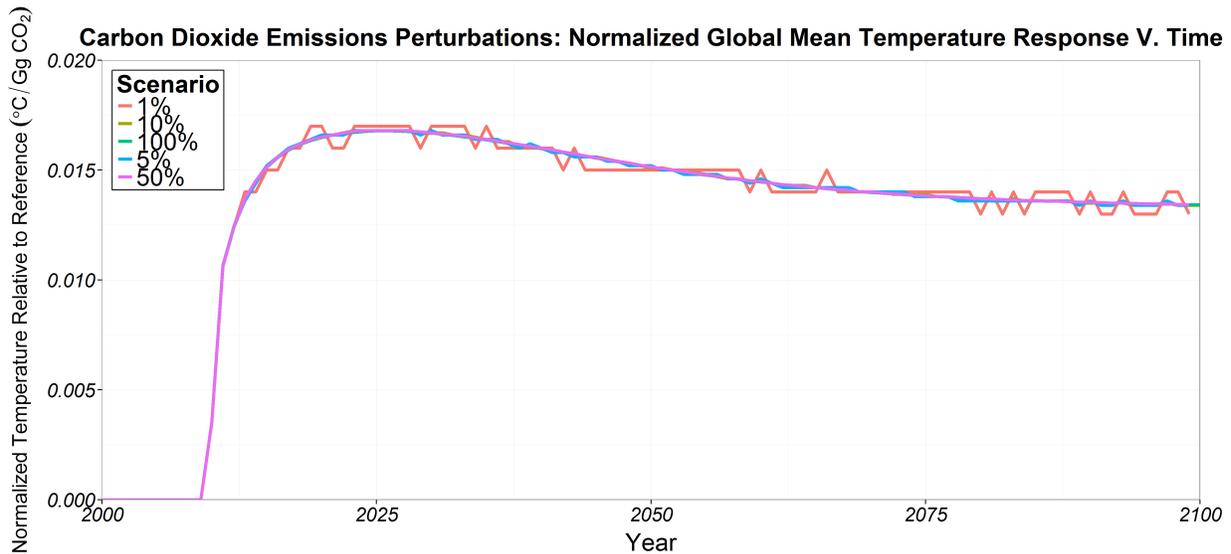


Figure 1: Normalized (by pulse size) global mean temperature response (perturbation - reference) from CO₂ emission perturbation of various sizes in 2010 using MAGICC 5.3.

Therefore, continuous use of multiple pulse sizes will not provide us with more information than initially expressed by a chosen size. For the purposes of this study used the 100% pulse size, or a doubling of the emissions or forcing value in a given year. The

remainder of this study follows various perturbation experiments conducted with MAGICC 5.3 and Hector v1.1 to investigate model behavior (Methodology).

The MAGICC 5.3 emissions perturbations yielded results interpreted using our understanding of the climate system representation within the model. We found that the response of the model to emissions perturbations varies in time scale, especially for longer lived GHGs, such as CO₂. This is seen in Figure 2, which shows the [CO₂] (Panel A), the total radiative forcing response (Panel B), and the GMST response (Panel C) of MAGICC 5.3 to various emission pulses in 2010. As expected, the BC (red) response is short-lived, while the CO₂ response (blue) does not return to the baseline before 2100. The responses result from the lifetimes of each of the chemical species studied, and also the interactions of each of these species in the climate system. While BC has short lifetime of approximately 4-12 days in the atmosphere (essentially instantaneous in MAGICC 5.3), CH₄ has a lifetime of 9 years, and CO₂ has an average lifetime of 100 years (Finlayson-Pitts and Pitts 1999). Other feedback mechanisms and climate interactions can further explain the features observed in Figure 2.

The behavior of the [CO₂] response in Figure 2 Panel A results from feedbacks within the carbon cycle; particularly the terrestrial uptake is responsible for the steady increase in concentration after the end of the century (blue). The connection between the [CO₂] response (Panel A, blue) and the terrestrial uptake response results from the increase in GMST as a response to a perturbation in CO₂ emissions in 2010 (Figure 2 Panel C, blue). The increased GMST leads to a rise in soil respiration, resulting in an increase in terrestrial uptake of CO₂ (dashed blue line) shown in Figure 3.

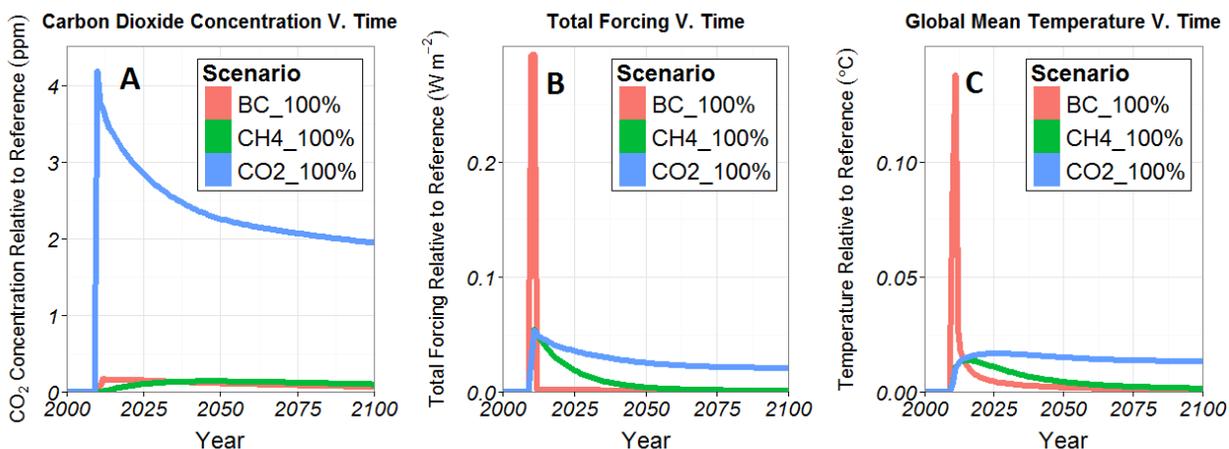


Figure 2: Emission impulse response (perturbation - reference) of different chemical species within MAGICC 5.3.

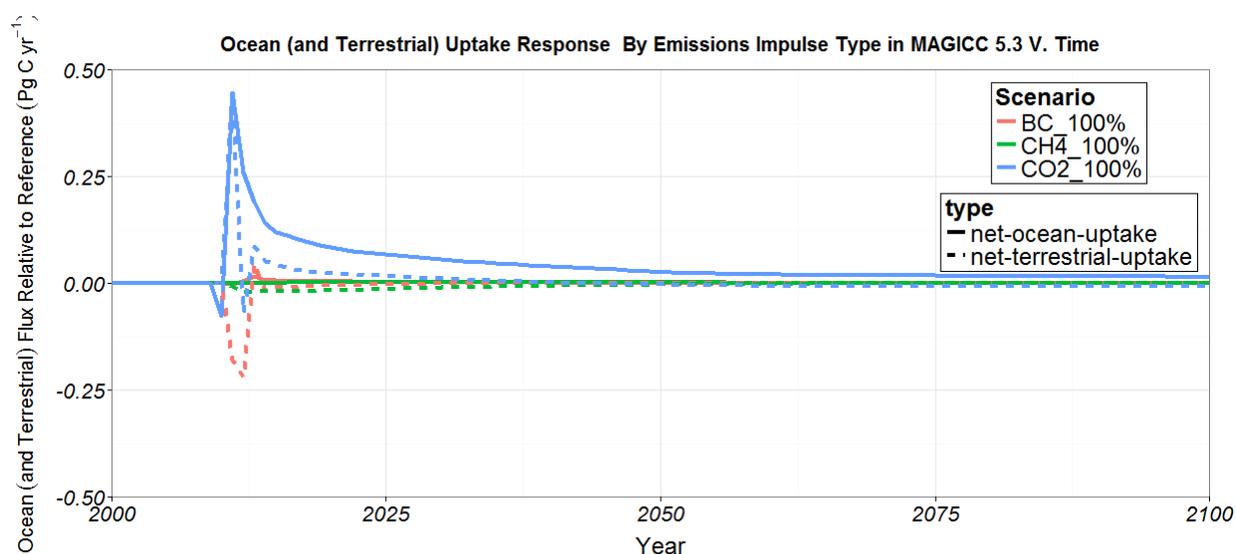


Figure 3: Ocean (and terrestrial) uptake response (perturbation - reference) in MAGICC 5.3.

The difference in the lifetimes of these chemical species results in a short-lived $[CO_2]$ response to a BC pulse (Figure 2). In MAGICC 5.3, the lifetime of BC is essentially instantaneous since the model runs on one year time steps. Therefore, the forcing response to a BC emissions pulse is also immediate (Panel B, red). These results also reassure our physical understanding of the climate system, as the $[CO_2]$ increases from a BC impulse as a

secondary effect from the GMST increase (Panel C, red). MAGICC 5.3 has a strong BC forcing response over land and this results in a GMST response that, again, peaks quickly and has a shorter response than the other chemical species, but it is the terrestrial feedback that is responsible for the sustained increase in $[\text{CO}_2]$ (Panel A, red).

Similarly, CH_4 emission perturbations impact $[\text{CO}_2]$ because within MAGICC 5.3, the final sink for CH_4 is fully oxidized CO_2 . Figure 2 Panel B shows CH_4 emission pulse responses (green) decaying more slowly than BC responses (red), but at a faster rate than CO_2 emission pulse responses (blue). Again, this response is related to the lifetime of the species and the interactions of the carbon cycle.

Figure 2 Panel B also shows that the BC emissions impulse GMST response (Panel C, red) is relatively linear with respect to the forcing response (Panel B, red). With the theoretical understanding in mind the question remains: how closely do these Green's functions approximate the climate system in MAGICC 5.3 and Hector v1.1? The Green's Function is generally able to represent the non-linearities in SCMs, but a test was conducted using the CH_4 emission impulse to test the CH_4 relationship. The GMST response (model response, blue) from a 100% pulse of CH_4 emissions in 2010 was compared to the integral of the forcing response (Green's function response, red, given by Eqn. 1) to produce Figure 4. The relationship is relatively linear, at least so far as represented by MAGICC 5.3, because the response of forcing is similar to that of the GMST response (Figure 4).

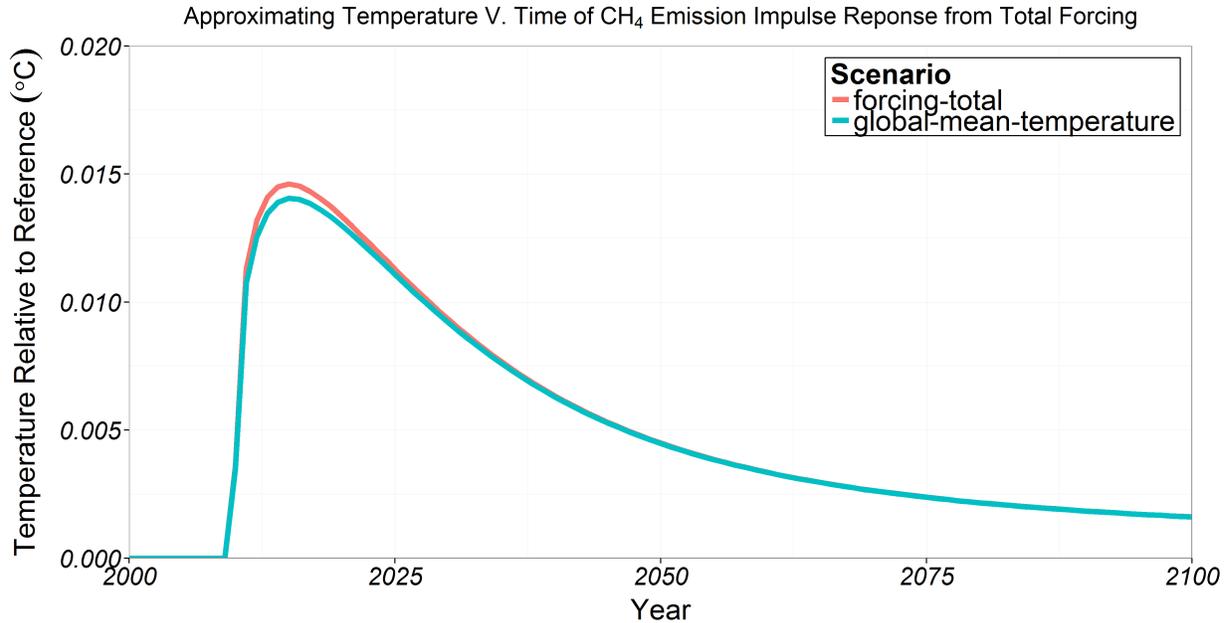


Figure 4: Methane emissions impulse temperature approximating from total forcing using the Green’s Function.

Finally, we conducted a $1\% \text{ yr}^{-1} [\text{CO}_2]$ test within MAGICC 5.3, as illustrated in Figure 5. The transient climate response was tested until $[\text{CO}_2]$ doubling (green) and quadrupling (blue), similar to stylized CMIP5 experiments. Figure 5 also shows a spontaneous 100% impulse of $[\text{CO}_2]$ in 2010 (red) for comparison. The GMST response in Figure 5 Panel C illustrates some features of the climate system, particularly the thermal lag in the ocean response to the perturbations. The transient climate response until doubling experiment has an increasing GMST response from the thermal inertia of the oceans, accounted for in the wider peak (red) in Figure 5 Panel C, compared to Figure 2 Panel C.

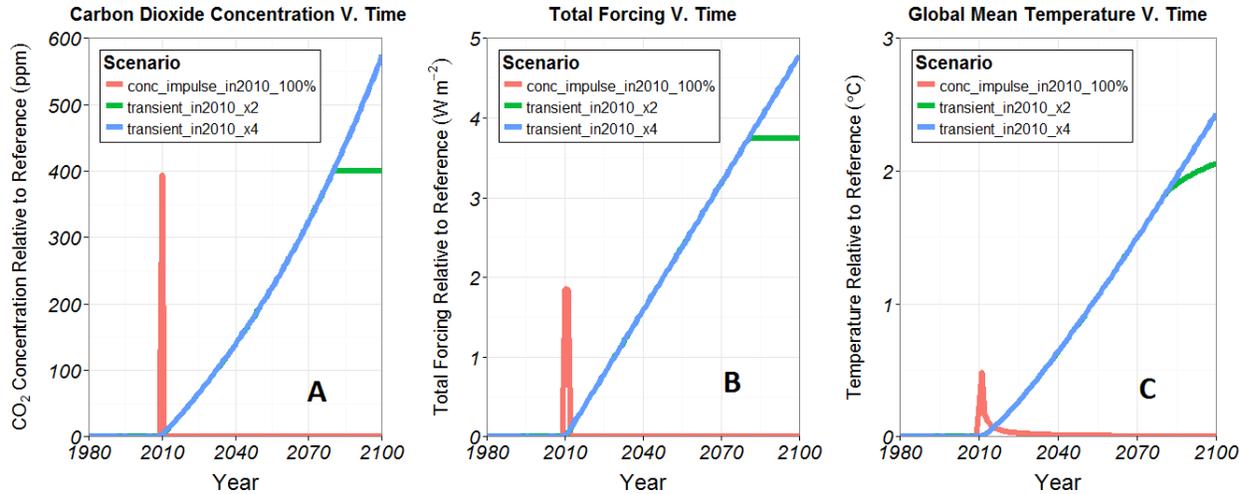


Figure 5: Transient climate response compared to CO₂ concentration impulse response (perturbation - reference) in MAGICC 5.3.

3.2 Impulse Response Tests: Hector v1.1

The same impulse response runs were conducted with Hector v1.1, a simple climate carbon-cycle model developed at the Joint Global Change Research Institute (JGCRI). The linearity of the GMST response to various perturbation sizes in Hector v1.1 was investigated. However, unlike the MAGICC 5.3 results (Figure 1), Figure 6 shows that Hector v1.1 is not generally approximated as linear above a 50% impulse in CO₂ emissions (e.g. the responses are not collinear). A 1% (red), 5% (blue), and 10% (yellow) increases produce an approximately linear GMST response, however, that does not hold for 50% (purple) or 100% (green) increases. It can be concluded that the impulse size in Hector v1.1 is consequential, unlike in MAGICC 5.3.

Subsequent results for Hector v1.1 were conducted for a 100% impulse to illustrate that the observed features were not a direct result of the non-linearity of the GMST response and for a direct comparisons between the two SCMs. Figure 2 showed the model response in

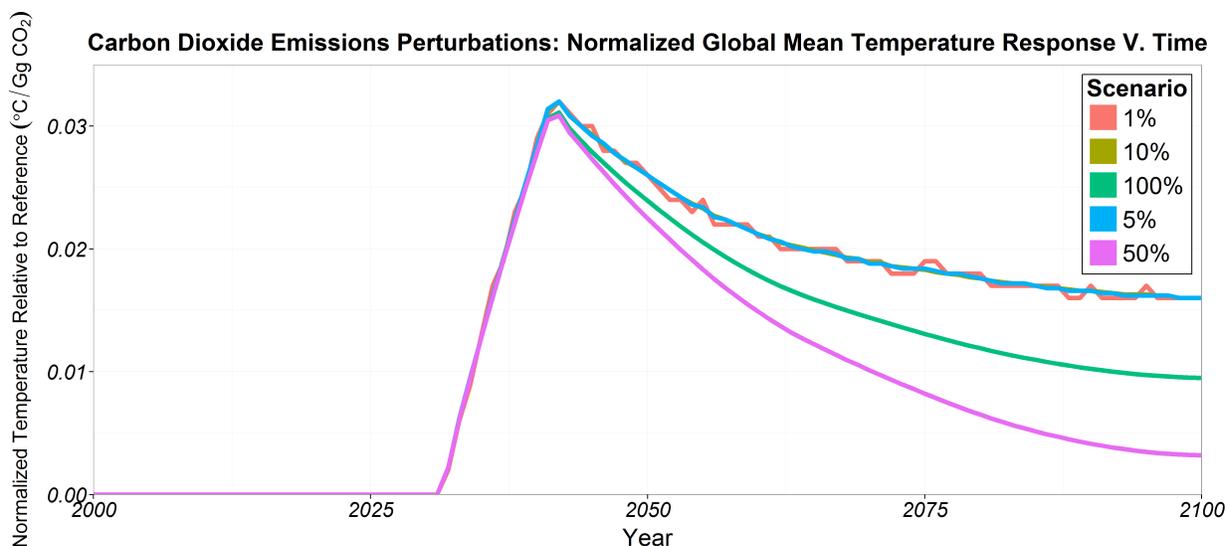


Figure 6: Normalized (by pulse size) global mean temperature response (perturbation - reference) from CO₂ emission perturbation of various sizes in 2010 using Hector v1.1.

MAGICC 5.3 to differing chemical species perturbations, and Figure 7 shows the same impulse response in Hector v1.1. The models behave similarly in the CO₂ impulse response (blue), but there is a lag in the GMST response, which begins in 2030 rather than 2010 when the impulse occurred (Figure 7 Panel C, blue). Further investigation discovered this was produced from a coding choice (see Appendix A). The CH₄ and BC responses differ substantially between the two SCMs. Figure 7 has different behavior in the CH₄ and BC response including negative impacts on the [CO₂] (Panel A, green and red, respectively) and a negative GMST response from a BC impulse (Panel C, red). Both of these features were unexpected (see Appendix B).

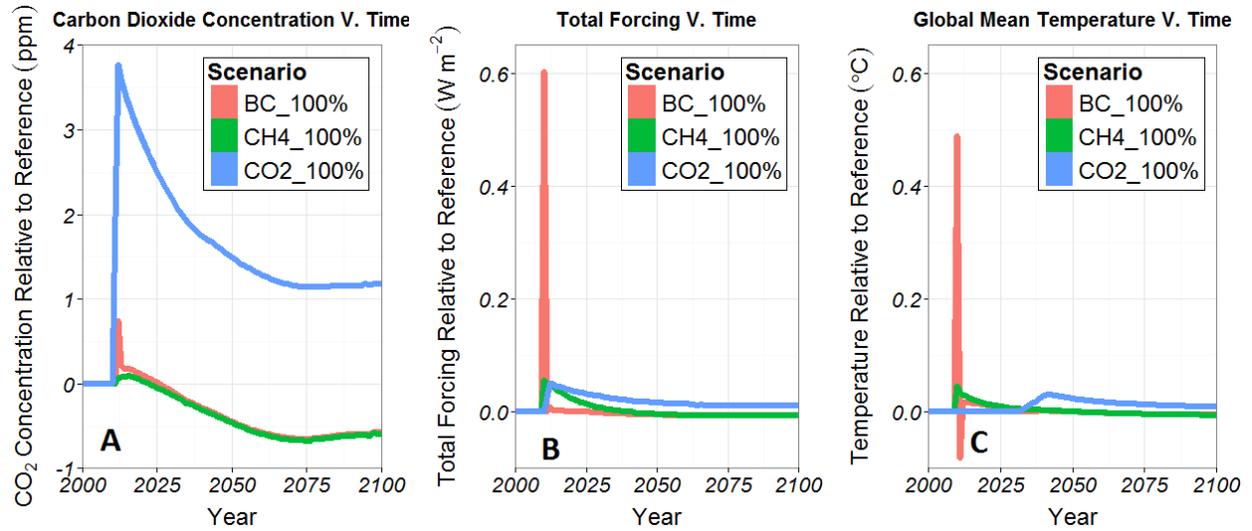


Figure 7: Emission impulse (100%) response (perturbation - reference) of different chemical species within Hector v1.1.

It was suspected the terrestrial and ocean fluxes within Hector v1.1 might contain further information about the unexpected results. Similar to Figure 3 for MAGICC 5.3, Figure 8 shows the flux of the terrestrial and ocean components to different chemical species perturbations. Comparing Figure 3 and Figure 8, the results from these two models are different and the causes of these differences were explored in the remainder of this study, particularly the behavior of the BC perturbation.

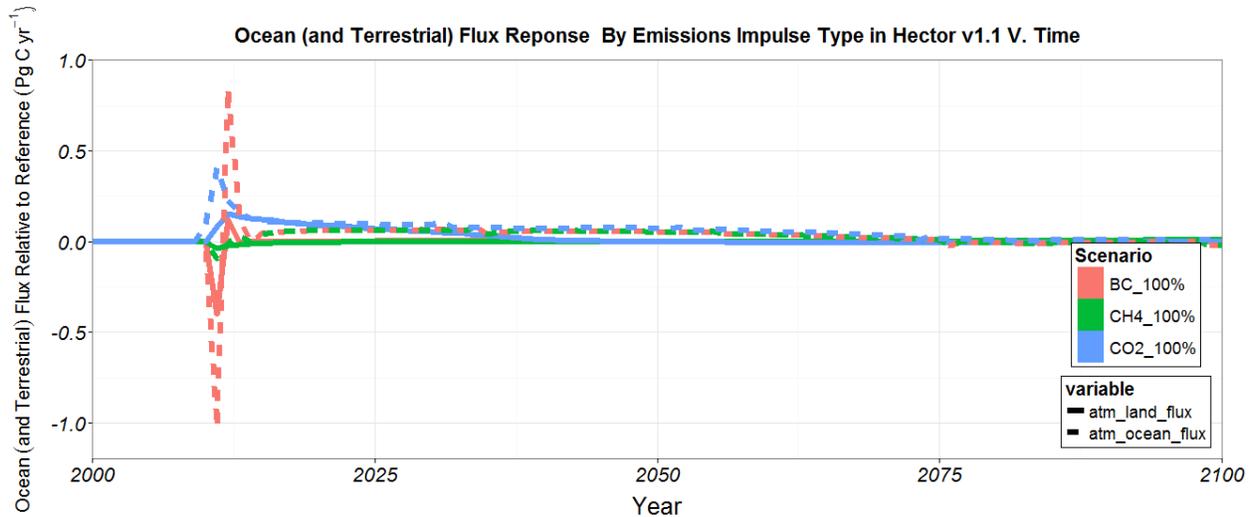


Figure 8: Ocean (and terrestrial) flux response (perturbation - reference) in Hector v1.1.

3.3 Hector v1.1 and MAGICC 5.3: Issue Exploration

In this section we conducted various tests in an attempt to explain the differences observed in Section 3.1 and 3.2. We tested numerous hypotheses to attempt to diagnose the behavior of Hector v1.1 compared to MAGICC 5.3 (our baseline). One known difference between the two SCMs is the temperature contrast over land and ocean and hemispheres. It was suspected this might account for some behavior in BC perturbation differences in the terrestrial and ocean uptake (Figures 3 and 8, red). Therefore, we disabled the hemispheres and land/ocean contrast in MAGICC 5.3 by altering the RLO (ratio of land-ocean warming) values. Figure 9 shows the MAGICC 5.3 response for a 100% BC emissions impulse using various RLO values including: 1.3 (base case, seen on previous figures), 1.2 (land warms 20% faster than ocean), 1.1 (land warms 10% faster than ocean), and 1.0 (land warms at same rate as ocean, ‘no hemispheres’). Figure 9 does not show similar behavior in the BC forcing response or GMST response to those observed in Hector v1.1 results (Figure 7), so this remains an open topic.

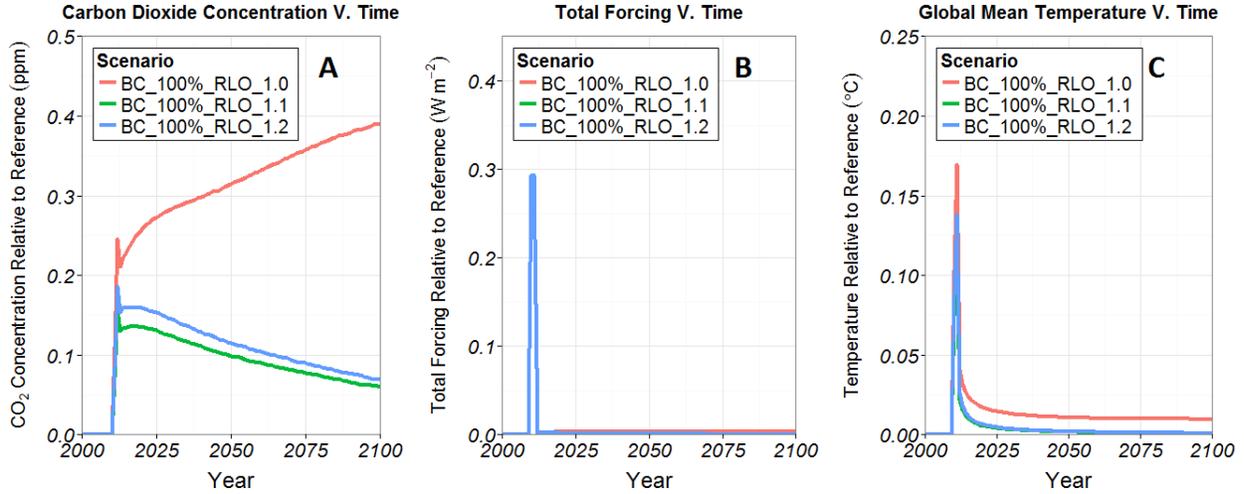


Figure 9: Emission impulse response (perturbation - reference) of BC with different RLO factors within MAGICC 5.3.

Further investigation into possible causes for differences between the two SCM responses revealed that the terrestrial-atmosphere flux in Hector v1.1 responds in a linear manner, while the ocean-atmosphere flux illustrates non-linear behavior (Figure 10). The 1% (red), 5% (blue), and 10% (yellow) impulses appear to have linear behavior (e.g. the lines overlay each other) in the ocean-atmospheric responses, but the 50% (purple) and 100% (green) impulse size are non-linear (e.g. distinct dashed lines). Furthermore, the ocean-atmosphere flux responses of these larger impulses are monotonic with a large level of noise in Hector v1.1. This will be further investigated within the Hector v1.1 ocean component, but this difference in linearity likely arises from the non-linear ocean carbon chemistry in Hector v1.1, compared to MAGICC 5.3 (Hartin et al. 2015).

These same non-linearities are not apparent in MAGICC 5.3 (Figure 11). Here, the ocean and land flux behave linearly for each CO₂ pulse size so that the individual responses are indistinguishable, except for the deterministic noise from the 1% pulse (dashed, red, Figure 1).

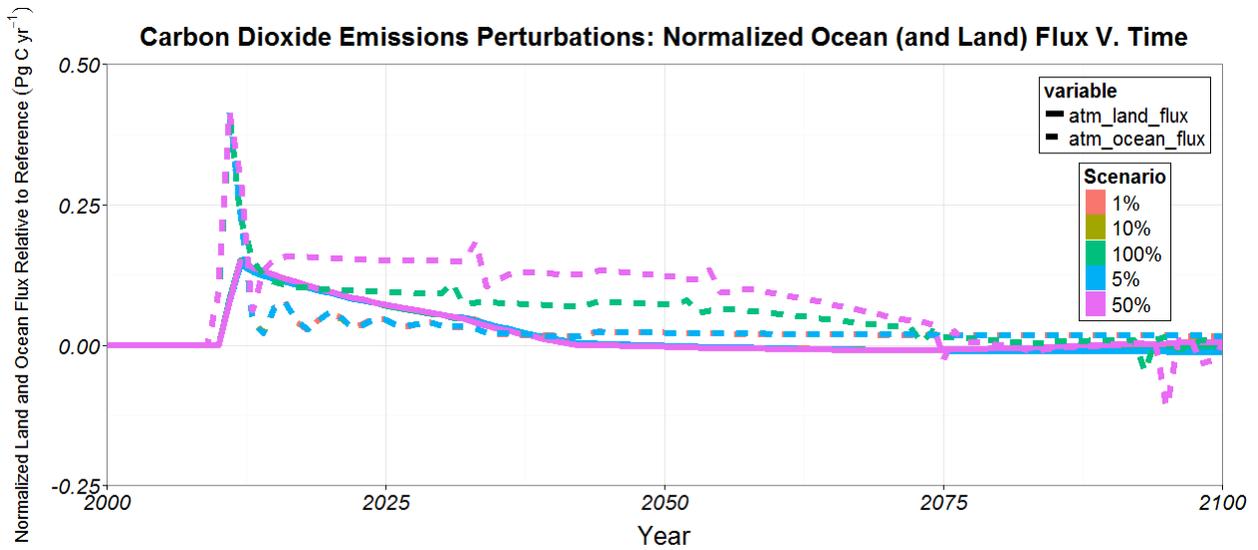


Figure 10: Ocean-atmosphere (and land-atmosphere) flux normalized by pulse size in Hector v1.1.

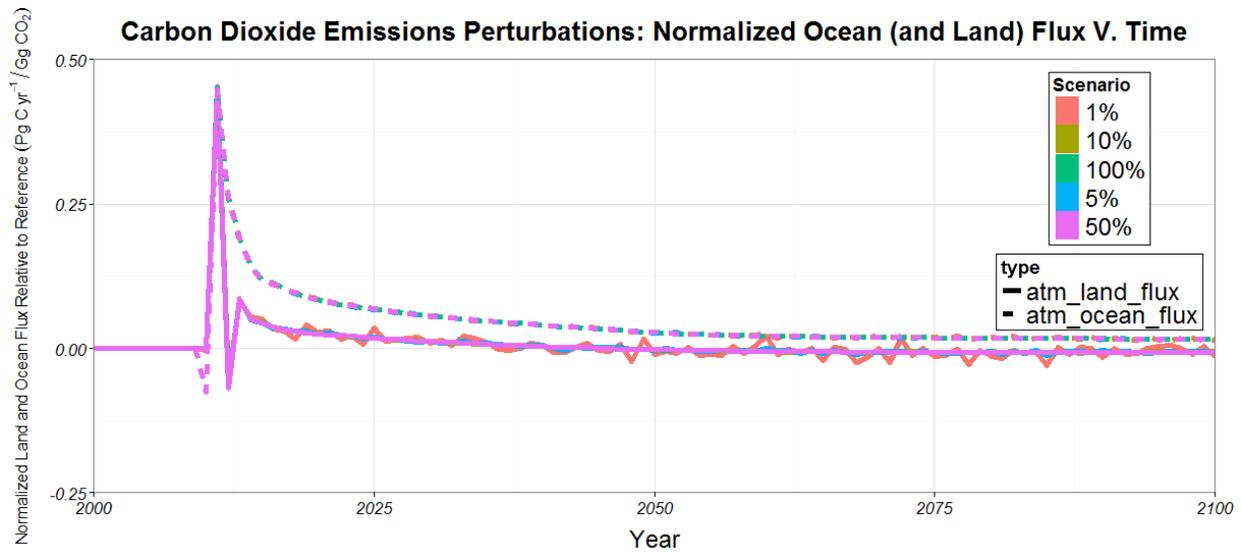


Figure 11: Ocean-atmosphere (and land-atmosphere) flux normalized by pulse size in MAGICC 5.3.

Chapter 4. Summary and Conclusions

To summarize this work, the following results show a series of direct comparisons of MAGICC 5.3 and Hector v1.1. Figure 12 shows the normalized GMST response in both SCMs. Notably, in Hector v1.1 the GMST response occurs in 2030, rather than in the year of

perturbation (e.g. 2010) like in MAGICC 5.3. After this study was concluded, investigation into the code revealed a lag in the climate system that resulted in the Hector v1.1 GMST response occurring at a later date than the time of perturbation (see Appendix A).

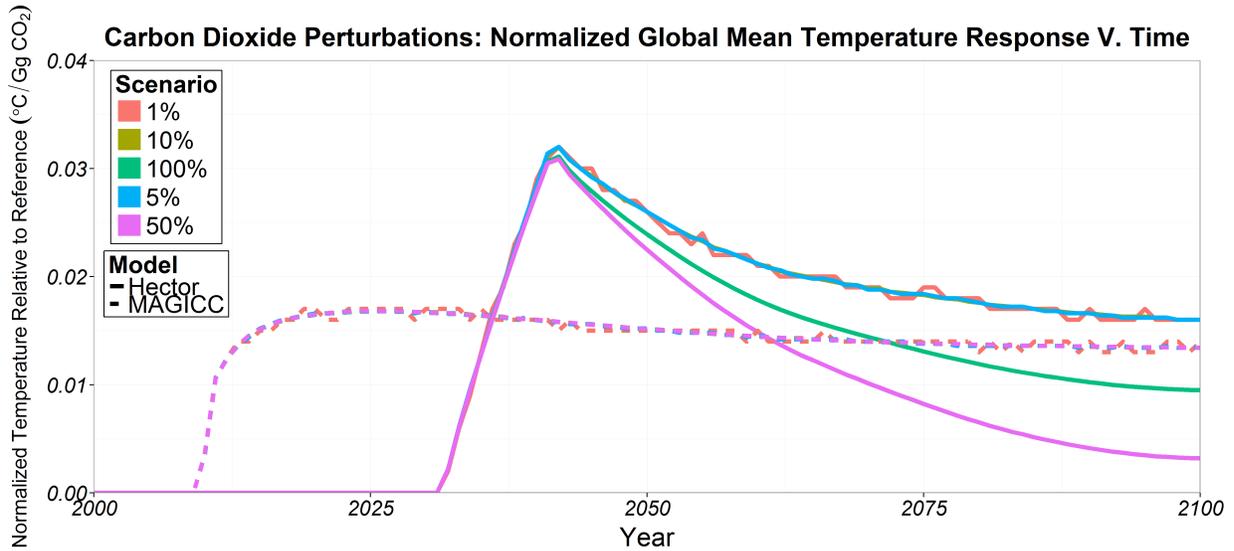


Figure 12: Normalized (by pulse size) global mean temperature response (perturbation - reference) from CO₂ emission perturbation of various sizes in 2010 using Hector v1.1 compared to MAGICC 5.3.

This delay is also observed in Figure 13 Panel C (blue), where the Hector v1.1 CO₂ temperature response occurs in 2030 (see Appendix A).

Figures 13 and 14 show the impulse response of the different chemical species in Hector v1.1 and MAGICC 5.3. Figure 14 has an expanded 2020-2100 axis to clearly show the relaxation times and the time lag from a CO₂ perturbation (blue).

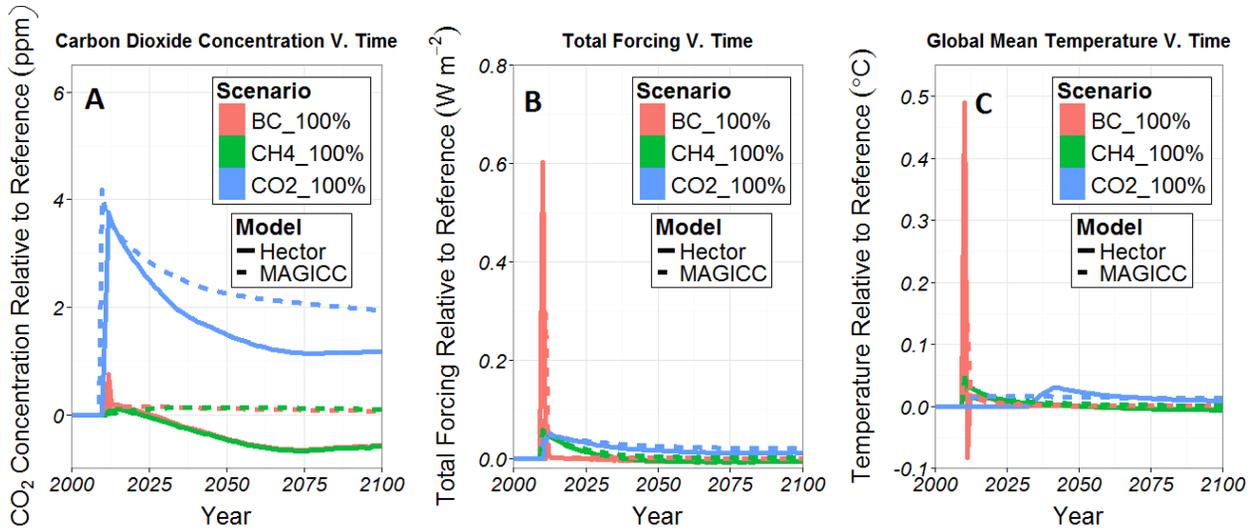


Figure 13: Emission impulse response (perturbation - reference) of different chemical species within Hector v1.1 compared to MAGICC 5.3.

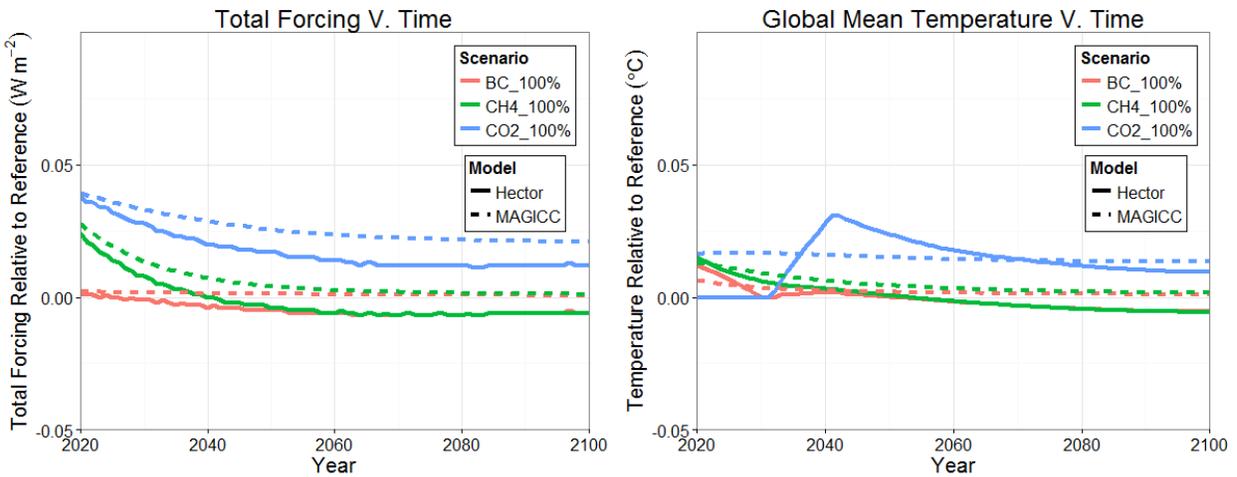


Figure 14: Emission impulse response (perturbation - reference) of different chemical species within Hector v1.1 compared to MAGICC 5.3 (2020-2100).

To further understand the model behavior, Figure 15 shows the scaled BC response and the CH₄ response in both Hector v1.1 and MAGICC 5.3. Rather than adding in the effects of the carbon cycle from CO₂ emissions perturbations, the CH₄ and BC emissions impulses only show the GMST response because they do not directly impact the carbon cycle. Results from Hector v1.1 show some odd behavior in the negative GMST response from a BC pulse,

and the strong negative $[\text{CO}_2]$ response from CH_4 perturbations, which is different from the response computed using MAGICC 5.3.

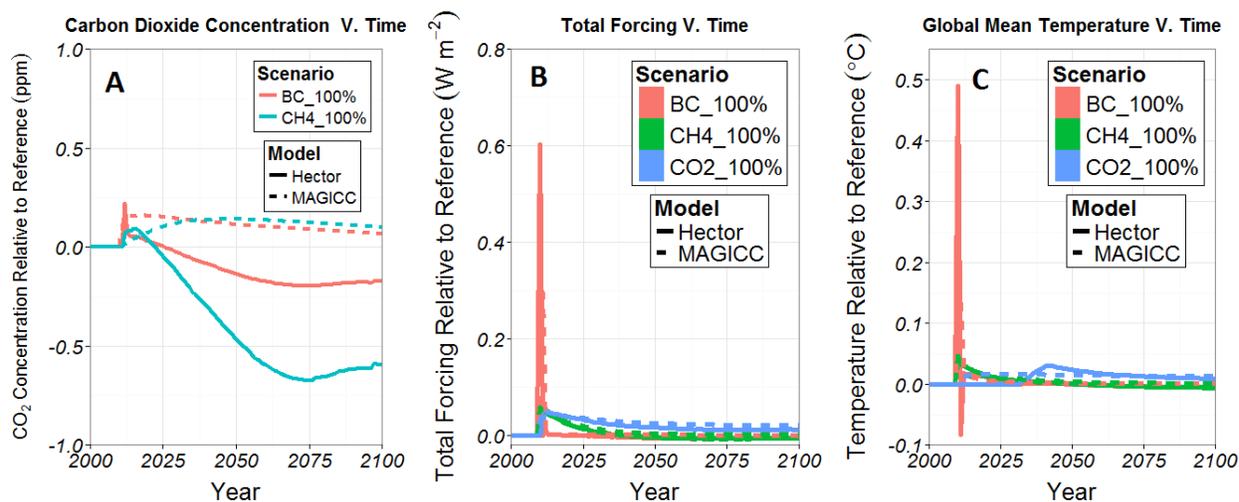


Figure 15: Emission impulse response (perturbation - reference) of BC (scaled by 30%) and CH_4 within Hector v1.1 compared to MAGICC 5.3.

In conclusion, this initial study was conducted to test the model response to perturbations in order to characterize the behavior of these two SCMs. We can see from this comparison study that the two SCMs, Hector v1.1 and MAGICC 5.3, have differences in their responses to perturbations from various chemical species (CO_2 , CH_4 , BC). Some of these differences require further investigation, such as the observed negative GMST response to a black carbon perturbation in Hector v1.1. Other differences were expected, and included non-linearities within Hector v1.1 likely resulting from the non-linear ocean carbon chemistry. The differences will be further explored as research continues, but this analysis highlights the importance of testing the fundamental carbon-cycle and climate responses of SCMs (National Academies of Sciences, Engineering, and Medicine 2016). Through model evaluation and comparison, fundamental perturbation tests remain a valuable tool to the modeling community interested in model improvement and refining model responses.

Chapter 5. Future Work

Several results highlighted in this work will be addressed in future work. The first feature needing future exploration is the negative GMST response in Hector v1.1 from a BC perturbation (See Appendix B). This is a non-physical result left unexplained by this work. In addition, in order to complete a comparison of Hector v1.1 and MAGICC 5.3, the TCR of both SCMs will be investigated. MAGICC 5.3 can currently be compared to CMIP5 transient runs, but updates to Hector v1.1 eliminated the ability to run with prescribed atmospheric CO₂. This feature will be added back into the model and Hector v1.1 will be compared to both MAGICC 5.3 and similar stylized CMIP5 runs.

The main objective of this future work is to clarify what role SLCF, such as CH₄ and BC, have in modifying the climate system by utilizing stylized experiments from CMIP5 with SCM emulations. Our approach will include exploring TCR within two stylized CMIP5 experiments (1% yr^{-1} [CO₂], abrupt 4XCO₂; Taylor et al. 2012) . Investigating the TCR can help us understand the realized warming and attribution to anthropogenic sources. Also, there is limited CMIP5 data exploring aerosol and ozone impacts on climate forcing (Shindell et al. 2014, Taylor et al. 2012). However, the two stylized experiment results can be explored to better understand the role of SLCF, such as aerosols and ozone, in the models. The analysis will be conducted at a sub-global scale because SLCF have a differential response over land. Given that the Northern Hemisphere (NH) has a larger percentage of the Earth's land mass than the Southern Hemisphere (SH), investigating the hemispheric differences and land/ocean response in the stylized experiments can elucidate the role SLCF play in global climate change.

Appendix

Appendix A: Temperature Lag in Hector v1.1

It was discovered that the Hector v1.1 GMST response has an lag effect, as observed in Figure 12. The authors of Hector v1.1 coded a 20-year lag (Figure 16, line 202) to better match the CMIP5 mean for initial testing (see Hartin et al. 2015). The code provided in Figure 16 shows the lines (196-210) within temperature_component.cpp (the temperature component) containing the lag effect and can be readily reviewed by others because Hector v1.1 is open source (available for download here: <https://github.com/JGCRI/hector>). After code fixes are applied, these impulse tests will be repeated.

```
196 // CO2 is subject to a lag effect, coded empirically here because a simple model
197 // like Hector doesn't account for all buffers and processes in the earth system
198 // We use a window (size CO2_WINDOW) CO2_LAG years in the past
199 const double FCO2_current = core->sendMessage( M_GETDATA, D_RE_CO2 ).value( U_W_M2 );
200 FCO2_record.set( runToDate, FCO2_current );
201
202 #define CO2_LAG 20
203 #define CO2_WINDOW 10
204 double FCO2_lagged_mean = 0.0; /* window mean of FCO2_past */
205 if( runToDate > core->getStartDate() + CO2_LAG ) {
206     for( int i=runToDate-CO2_LAG-CO2_WINDOW; i<runToDate-CO2_LAG; i++ ) {
207         FCO2_lagged_mean += FCO2_record.get( i );
208     }
209     FCO2_lagged_mean /= CO2_WINDOW;
210 }
```

Figure 16: Hector v1.1 code from temperature-component.cpp.

The impulse work conducted in this study brings to light the need for robust models running all conditions.

Our assumption in Hector v1.1 is that the ocean heat uptake is a function of the GMST and declines following a sigmoid model. Here, we assume heat is advected from the surface to deep rather than diffused, hence the choice in coding. Thus, given a pulse of heat to the atmosphere, the ocean will uptake a portion of that heat. Given time, the heat in the ocean surface will be advected away from the surface layer, to the deep. The heat uptake a year after the pulse will be slightly less than ‘normal’ because all of that heat has not advected out of the surface layer. We can see this when comparing the orange (BC perturbation) and blue lines (reference) in Figure 18. The initial heat uptake is larger compared to the reference, followed by less heat uptake, before returning to baseline values (also seen in Figure 19). Better representation of ocean heat fluxes is currently being explored.

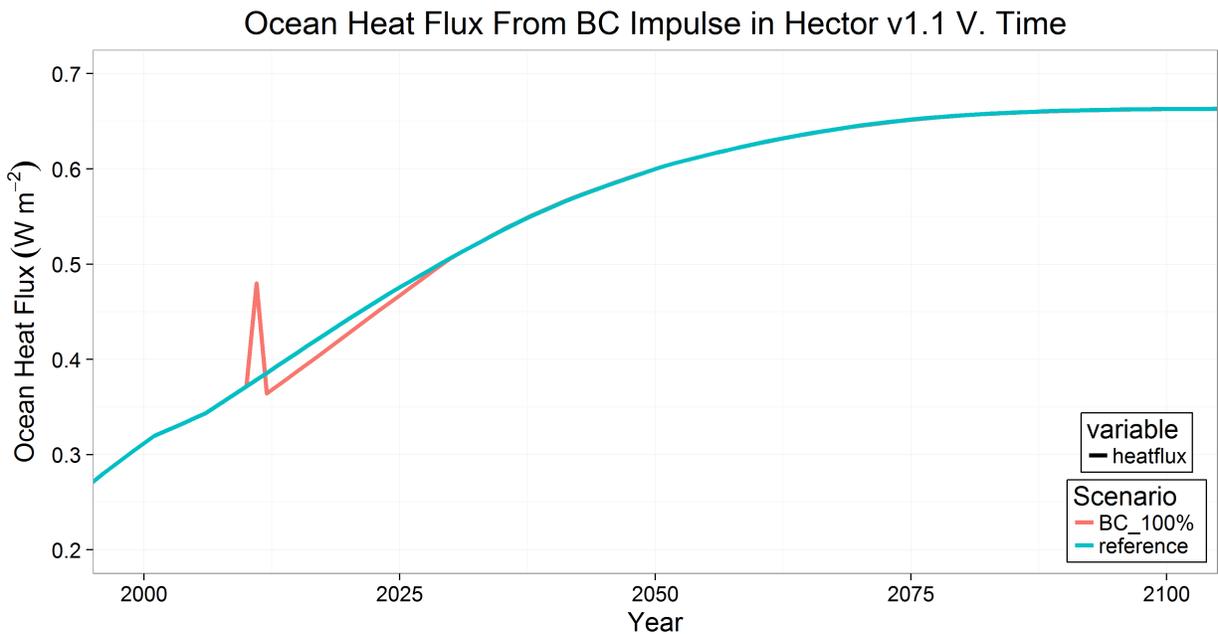


Figure 18: Ocean heat flux of black carbon emission impulse within Hector v1.1 with reference scenario.

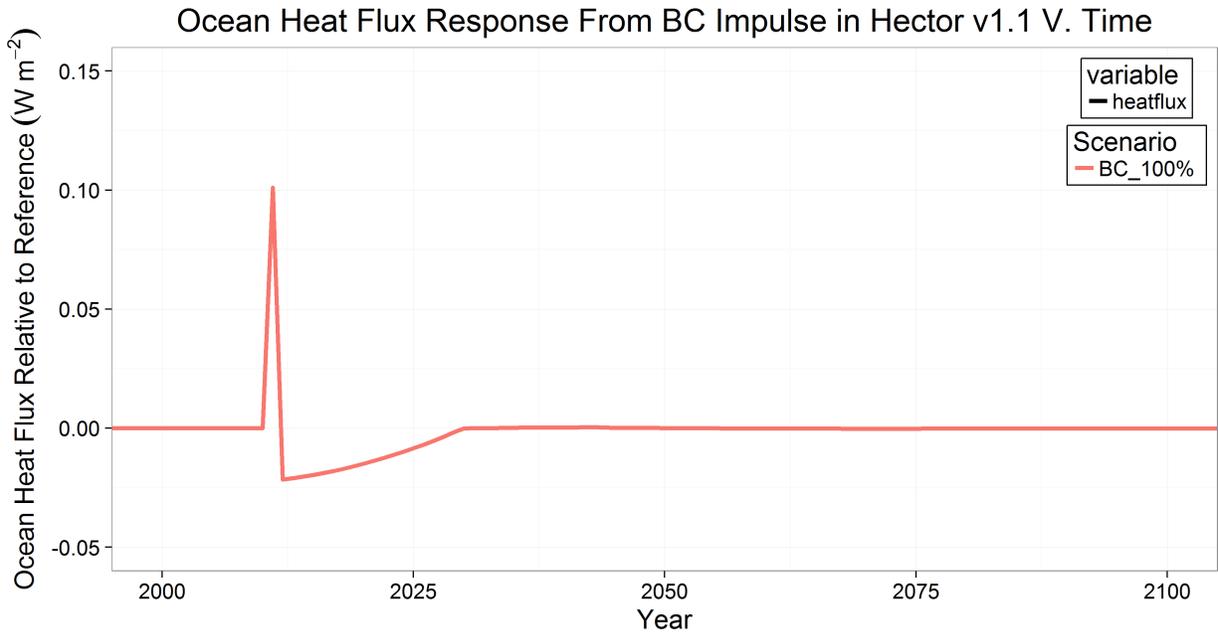


Figure 19: Ocean heat flux response (perturbation - reference) of black carbon emission impulse within Hector v1.1.

Appendix C: Non-Monotonic and Non-Linear Nature in Hector

v1.1

Based on the non-linear and non-monotonic nature of the Hector v1.1 ocean component (Figure 10) and the further investigation into the ocean heat flux (Figure 18 and Figure 19), the high latitude (HL) and low latitude (LL) of ocean carbon flux were investigated to determine which ocean box was producing the non-linear and non-monotonic behavior. It was discovered, based on Figure 20, that both the HL and LL ocean box (solid lines and dashed lines, respectively) are responsible for this behavior.

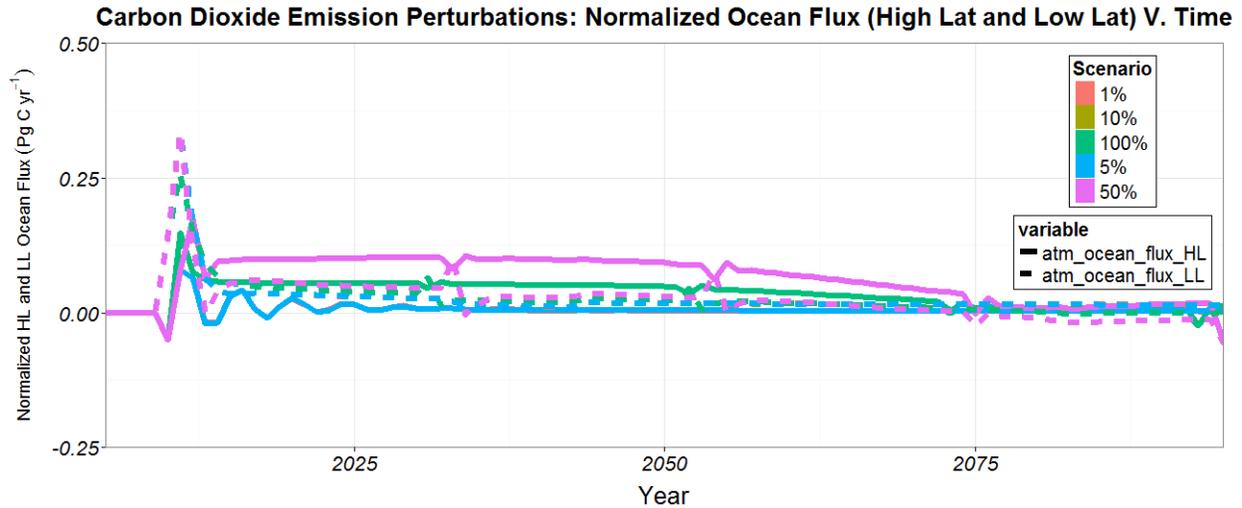


Figure 20: Normalized (by pulse size) ocean flux response (perturbation - reference) in the High Lats (HL) and Low Lats (LL) from CO₂ emission perturbation of various sizes in 2010 using Hector v1.1.

We hypothesize the non-monotonic nature in ocean component in Hector v1.1 arises from saturation in the carbonate system, making it difficult for the system to uptake more atmospheric CO₂. Therefore, under a 50% CO₂ pulse, the ocean take up more CO₂ than under a 100% CO₂ pulse. However, these findings will require further investigation by members of the Hector development team outside the current scope of this work.

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