HIRM v1.0: A hybrid impulse response model for climate modeling and uncertainty analyses

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Abstract. Simple climate models (SCMs) are frequently used in research and decision-making communities because of their flexibility, tractability, and low computational cost. SCMs can be idealized, flexibly representing major climate dynamics as impulse response functions, or process-based, using explicit equations to model possibly nonlinear climate and Earth system dynamics. Each of these approaches has strengths and limitations. Here we present and test a hybrid impulse response modeling framework (HIRM) that combines the strengths of process-based SCMs in an idealized impulse response model, with HIRM's input derived from the output of a process-based model. This structure enables the model to capture some of the major nonlinear dynamics that occur in complex climate models as greenhouse gas emissions transform to atmospheric concentration to radiative forcing to climate change. As a test, the HIRM framework was configured to emulate the total temperature of the simple climate model Hector 2.0 under the four Representative Concentration Pathways and the temperature response of an abrupt four times CO_2 concentration step. HIRM was able to reproduce near-term and long-term Hector global temperature with a high degree of fidelity. Additionally, we conducted two case studies to demonstrate potential applications for this hybrid model: examining the effect of aerosol forcing uncertainty on global temperature, and incorporating more process-based representations of black carbon into a SCM. The open-source HIRM framework has a range of applications including complex climate model emulation, uncertainty analyses of radiative forcing, attribution studies, and climate model development.

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1 Introduction

Climate models encompass a diverse collection of approaches to representing Earth system processes at various levels of complexity and resolution. The most complex are the Earth System Models (ESMs): highly detailed representations of the physical, chemical, and biological processes governing the Earth system at high spatial and temporal resolution (Hurrell et al. 2013). These models are computationally expensive and therefore can only be run for a limited number of scenarios. Slightly less complex and more computationally efficient are the Earth System Models of Intermediate Complexity (EMICS) (Stocker, 2011). Finally, Simplified Climate Models (SCMs) sacrifice process realism but are computationally inexpensive (van Vuuren et al., 2011). Although SCMs are generally low resolution in space and time, they have a wide range of applications including emulation (Dorheim et al. 2019); probabilistic estimates demanding thousands of separate model runs (Stainforth et al. 2005;

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Webster 2012); factor separation analysis (Mheel et al., 2007); and Earth system model development and diagnosis (Meinshausen et al., 2011).

SCMs vary in complexity. Process based SCMs such as Hector (Hartin et al. 2015) and MAGICC (Meinshausen et al., 2011) consist of systems of equations that represent, albeit in highly simplified form, carbon cycle and climate dynamics. Whereas some SCMs are more abstract, consist of fewer highly parameterized equations. Some of the more idealized SCMs (*sensu* Millar et al. 2017) use impulse response functions (IRFs) to approximate climate dynamics (Millar et al., 2017). IRF-based SCMs are themselves diverse; some are highly idealized, such as the Impulse Response Function used in the Fifth IPCC Assessment Report (Myhre et al., 2013) (AR5_IR), while others are quasi process-based, only using IRFs to approximate linear climate dynamics, with the rest of the climate system represented by process-based equations (Strassmann and Joos 2018; Smith et al. 2018; and Joos and Bruno 1996).

One of the fundamental differences between process-based SCMs and idealized IRF-based SCMs is in their representation of the important nonlinear climate dynamics occurring during the evolution of emissions to climate impacts. Process-based models (whether SCMs or ESMs) have equations that represent emissions accumulating as concentrations, which in turn affect the energy (radiative forcing) resulting in climate changes (most prominently, temperature change) (Harvey et al. 1995; Claussen et al. 2002). The system of equations used by process-based SCMs represents some, though not all, of the more complex and often nonlinear dynamics observed in the Earth system. These dynamics include interactions between atmospheric chemical constituents (Wigley et al. 2002); non-linear relationships between greenhouse gas concentrations and energy absorption, i.e. radiative forcing (Shine et al. 1990 and Myhre et al. 1998); and carbon-climate feedbacks such as ocean surface CO_2 uptake (Wenzel et al. 2014, Tang Riley 2015, and Heinmann and Reichstein 2008). Comprehensive process-based SCMs such as Hector and MAGICC have thousands of lines of code and take significant effort to expand. On the other extreme, simple impulse response models can be expressed in a few equations and are readily implemented, but these simplifications can produce biases in results (van Vuuren et al. 2011, Schwarber et al. 2019). We discuss here a framework that can be used as a testbed for SCM development and analysis.

In this manuscript we document and demonstrate a highly idealized IRF-based framework. This modeling framework is configured using output from a process-based model to capture nonlinear and complex climate dynamics, we refer to it as a hybrid impulse response modeling (HIRM) framework. HIRM was configured using the open source, object-oriented, process-based SCM Hector v 2.3.0, although in theory it could potentially use information from any climate model (ESM, EMIC, SCM). The first two experiments in this paper demonstrate HIRM's ability to accurately reproduce global mean temperature, including the temperature response to large climate system perturbations. We also demonstrate the potential utility of this framework in an uncertainty analysis and examine how changing the response function for black carbon impacts HIRM output. We discuss the implications of these results as well as potential future uses of this framework.

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2 Methods

2.1 Parent Model Description

In this study we used Hector v 2.3.0 as the parent model, providing both of HIRM's primary and only inputs. We selected Hector because it is open source, well documented, fast-executing, and has a structure that makes it easy to obtain 'clean' IRFs from model runs (Schwarber et al. 2019). (As noted above, however, HIRM can be coupled with any parent model that can provide its inputs.) Hector has been well documented (Hartin et al. 2015), but we provide a brief summary here.

Hector (Hartin et al. 2015) is an open source, process-based SCM carbon-climate model available at https://github.com/jgcri/hector. The model is written in C++ and has an object-oriented structure, allowing for substitutions of different model components; it has both internal and external automated testing, e.g. enforced unit-checking, that provides robustness and quality assurance. Hector models carbon and energy flows between the ocean, atmosphere, and terrestrial biosphere, starting with a preindustrial steady-state system that is then perturbed by anthropogenic emissions provided as input files. The model runs on an annual timestamp, although the carbon cycle as an adaptive-timestep solver to ensure smooth numerical changes when fluxes (primarily ocean uptake) are large. The terrestrial carbon cycle is divided into biota, litter, and soil across multiple biomes; the ocean features surface, intermediate, and deep pools in different hemispheres, with heat uptake governed by an implementation of the DOECLIM (Kriegler 2005; Urban et al. 2014) 1-dimensional heat diffusion sub-model. Hector models the dynamics of 37 different radiative forcing agents. The total radiative forcing in turn affects global temperature change, with all of Hector's radiative forcing agents exhibiting the same temperature response to change in radiative forcing. In effect, Hector can be considered to interpret forcing assumptions as Effective Radiative Forcing values, which are more closely related to surface temperature changes than the previously used values for stratospheric-adjusted radiative forcing (Richardson et al. 2019). This has no impact on the model dynamics that are our focus here, and only impact how numerical values are selected as input settings. Note that Hector also assumes that the temporal shape of the response function is the same for all forcers, a simplifying assumption that has consequences for HIRM configuration, but also the consequences of which we examine below.

2.2 HIRM Description

HIRM's total atmospheric temperature response is calculated as the sum of the Green's function of a temperature response to a radiative forcing perturbation with radiative forcing time series, an approach taken by many SCMs (Joos et al. 1999; Van Vuuren 2011; Millar et al. 2015; and Boas 2006). By relying on a process-based climate model to compute RF values, HIRM is able to use a linear IRF in a simple impulse response model and capture the major nonlinear dynamics between the emissions to radiative forcing calculations by using radiative forcing time series as input data.

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HIRM calculates the atmospheric temperature change from preindustrial temperature (T) as the sum of the temperature contribution from individual forcing agents T_i Eq. (1):

$$T(t) = \sum_{i=1}^{n} T_i(t), \qquad (1)$$

Here the individual temperature contribution is equal to the convolution of the radiative forcing time series RF_i with the temperature response to a radiative forcing pulse IRF_i for a single radiative forcing agent Eq. (2).

$$T_i(t) = \int_{t_0}^{t} RF_i(t')IRF_i(t-t')dt', \qquad (2)$$

The method we used to obtain RF_i and IRF_i for HRIM relies on output from a parent process-based model. The subsequent sections discuss how we obtained RF_i and IRF_i specifically from Hector. It is important to note that while HIRM can be set up with unique IRFs for each radiative forcing agent (as demonstrated below), this was not done in this application since Hector uses one IRF for all species.

HIRM is an open source R package (https://github.com/jgcri/hirm) with Doxygen-style comments, unit tests, and online documentation via pkgdown (Wickham and Hesselberth 2020). The online documentation available at https://jgcri.github.io/HIRM/ documents all of the package functions and links with a vignette(example) that demonstrates how to set up and run HIRM. The package contains all of the IRFs and RF inputs used in this manuscript that can be used in a customizable configuration matrix to set up and run HIRM.

2.3 IRF Derivation

As previously mentioned, one of Hector's assumptions is that all of Hector's radiative forcing agents elicit the same temperature response to a change in radiative forcing. Even though HIRM can use a unique IRF for each radiative forcing agent, for the purposes of HIRM validation exercises in this study, HIRM's setup must be analogous to that of its parent model Hector. In this study we configured HIRM with a single IRF that characterizes Hector's temperature response to all of its 37 radiative forcing agents, derived from a reference run and a black carbon (BC) emissions perturbation run of Hector. Hector, BC emissions are converted directly to radiative forcing, and therefore an emissions pulse of BC is analogous to a radiative forcing pulse. BC was chosen as the forcing agent since there are no gas-cycle or forcing interactions with other species within Hector, making it straightforward to derive the IRF, but other forcing agents could have been selected for the perturbation run. During the reference model run Hector was driven with the RCP 4.5 scenario, while for the perturbation model run BC emissions were doubled relative to RCP 4.5 BC emissions in a single year. RCP 4.5 CO_2 concentrations were prescribed during these runs, suppressing Hector's normal carbon cycle temperature feedbacks.

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For the two validation experiments we did not include carbon-cycle climate feedbacks into the IRF as we wanted to examine the relative importance of non-linearities in emission to forcing calculations, at least as represented in Hector, as compared to non-linearities in Hector's forcing to temperature calculations (as represented within DOECLIM). For this reason the IRF should represent only the response of temperature to radiative forcing; otherwise, the temperature response from these feedback mechanisms would be incorporated into the IRF, which would then be doubled-counted as forcing time series are being used as inputs. For the replication experiments we also focus on reproducing Hector temperature without carbon-climate feedbacks. Other applications of HIRM may require IRFs that include the temperature response from carbon-cycle feedbacks.

The temperature response ($T_{response}$) to the BC emissions perturbation is equal to the difference between the reference (T_{ref}) and perturbation temperature (T_p) Eq. (3), with the perturbation occurring at year t_0:

$$\mathrm{T_{response}}(\mathrm{t}-\mathrm{t_0}) = \mathrm{T_p}(\mathrm{t}-\mathrm{t_0}) - \mathrm{T_{ref}}(\mathrm{t}-\mathrm{t_0}), \quad (3)$$

The temperature response to a radiative forcing perturbation was calculated by dividing the temperature response to the emissions perturbation by the size of the radiative forcing pulse Eq. (4). The size of the radiative forcing pulse (X_y) was set equal to the difference in radiative forcing between the reference and emissions perturbation runs (described in the paragraph above) in the perturbation year:

$$\mathrm{IRF_i}(\mathrm{t}-\mathrm{t_0}) = \mathrm{T_{response}}(\mathrm{t}-\mathrm{t_0})/\mathrm{X_y}, \quad (4)$$

This IRF had a length of 300 years, in order to ensure the IRF was long enough to be convolved with the RF inputs; the end of the IRF was extrapolated with an exponential decay function to a length of 3000 with a decay constant of 0.20. Extending the length of the IRF prevents the IRF from being padded with zeros and having to truncate the RF inputs.

The majority of Hector's temperature response to a radiative forcing pulse occurs within the first 50 years after the perturbation (Fig. 1). The strongest response occurs during the perturbation year itself, with a maximum value of 0.09 (°C W^{-1}m^{-2}); by year 35 the temperature response has decreased by 97% and continues to approach zero for the remainder of the IRF. This IRF is used in both of the validation experiments and case studies except where noted.

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3 Validation Experiments

3.1 Replication of RCP Results

Emulation is used to validate HIRM by illustrating that the HIRM framework reproduces the dynamics of a process-based SCM with a minimal loss of information. If HIRM can accurately reproduce or emulate the atmospheric temperature of a more complex, process-based-model such as Hector, then we assume that HIRM is able to capture important non-linear dynamics of the climate system using this setup, at least to the extent these are captured in the SCM. Conversely, if HIRM is unable to reproduce Hector's global temperature outputs, this would indicate that important processes are not being captured by the HIRM framework.

In the first validation experiment, HIRM was set up to reproduce Hector temperature for RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5. HIRM was configured for each RCP scenario with a single IRF derived from Hector (fig. 1) together with a complete set of time series from Hector's 37 radiative forcing agents. The radiative forcing time series for these validation experiments came from Hector output from RCP 2.6, 4.5, 6.0, and 8.5 with prescribed CO_2 concentrations. The global mean temperature outputs from Hector driven with RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5 were saved and used as validation data for HIRM.

HIRM was able to emulate Hector's temperature for the four RCPs with a minimal loss of information (Fig. 2a). The difference between HIRM and Hector total temperature, measured as the root mean squared error (RMSE), was 1.3 x 10^{-9} °C (Fig. 2a) for each RCP scenario. The cumulative percentage difference between HIRM and Hector temperature was 0 % (rounded from 1.0 x 10^{-5}; other 0% results are similar) for each RCP scenario.

3.2 Replication of 4X CO_2 Results

The second validation experiment tested HIRM's ability to reproduce Hector's temperature response to an abrupt four times CO_2 concentration step. The abrupt four times CO_2 concentration step is a test commonly used by climate modelers to understand the climate system's response to CO_2 (Taylor et al. 2012). In this experiment HIRM was set up with the Hector derived IRF and a RF input from an abrupt four times CO_2 concentration step. The radiative forcing time series was obtained from Hector runs following the CMIP5 protocol (Taylor et al. 2012). HIRM's radiative forcing time series input was the difference in Hector radiative forcing from Hector driven with a constant CO_2 concentration of 278 ppm and Hector driven with a CO_2 concentration of 278 ppm until year 2010 when the CO_2 concentration increased by a magnitude of four and remained constant for the rest of the run. The difference in Hector's global mean temperature anomaly between the constant reference run and the perturbed step run was then compared with HIRM's output.

HIRM reproduced Hector's abrupt four times CO_2 concentration step temperature response with a high degree of accuracy (Fig. 2b). The RMSE between HIRM and Hector temperature output from the abrupt CO_2 concentration step was 1.5 x 10^{-19} °C with a cumulative percent difference of 0%. The abrupt CO_2 concentration step is a standard diagnostic test used to examine

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climate model responses (Taylor et al. 2012; Eyring et al. 2016). Since HIRM was able to accurately emulate Hector's temperature response to a large step perturbation we conclude that the majority of the nonlinearities within Hector are occurring during the emissions-to-radiative forcing portion of the emissions-to-temperature causal chain. While this is to be expected from the general principles of SCMs, it nonetheless provides a useful check that our understanding of the parent model's behavior is correct.

4 HIRM Application Case Studies

4.1 Aerosol Uncertainty Case Study

Uncertainties in the magnitude of historical and future radiative forcing effects continue to be a crucial challenge for climate science research, and this is particularly true for aerosol effects (Forest 2018). In this first case study HIRM was used to explore a range of future temperature change when accounting for uncertainty in some aerosol radiative forcing effects, specifically black carbon (BC), organic carbon (OC), indirect SO_2 effects (SO_2i), and direct SO_2 effects (SO_2d). To do so, HIRM was again set up to recreate Hector's RCP 4.5 temperature. In this analysis, BC, OC, SO_2i, SO_2d RF inputs were varied. (Aerosol cloud indirect effects are represented in Hector as a function of SO_2 emissions only, so we refer to that as SO_2 indirect forcing.) We present a simple demonstration of the model in this case study and note that we have not produced probabilistic results but an illustrative range of temperature pathways that result from aerosol uncertainties (e.g. Smith and Bond 2014). A full probabilistic analysis would also involve varying additional parameters, such as climate sensitivity, ocean heat update, and carbon-cycle parameters.

The aerosol uncertainty scalers were generated from the 2011 aerosol radiative forcing ranges reported in IPCC AR5 8.SM table 5 (Myhre et al. 2013). The BC, OC, SO_2i, and SO_2d radiative forcing IPCC ranges were individually sampled at intervals of 0.04 W m^{-2} in 2011 (Table 1), resulting in a total of 29000 times uncertainty scalar combinations. Default HIRM 2011 BC, OC, SO_2i, and SO_2d radiative forcing values were then divided by the values sampled from the respective IPCC ranges to obtain the uncertainty scalers.

HIRM was set up to run every possible combination of the scaled RF time series, a total of 29000 times. This created an ensemble of uncertainty runs, whose results were constrained (i.e., filtered) by historical radiative forcing and temperature. HIRM total radiative forcing was constrained to match IPCC historical estimates in radiative forcing and temperature change. The 2011 aerosol (SO2i, SO2d, BC, + OC) radiative forcing was constrained to pass through an uncertainty range [-1.66 to 0.14 Wm-2]. (Similar to Myhre et al. 2013, but adjusted to account for nitrate and dust forcing and empirical constraints, see discussion in Smith and Bond 2014). HIRM temperature trend was calculated as the slope of a linear regression and then

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compared to the observed temperature trend range of [0.65 to 1.1] °C over 1880–2012 reported by Hartmann et al. 2013. Cases that did not meet these constraints were removed (see Fig. 3).

We found that the historical constraints had an unequal impact on the scaled radiative forcing impacts. The temperature at the end of the century for the unconstrained ensemble ranged over 2.5°C – 3.1°C; incorporating the historical constraints into the uncertainty analysis narrowed uncertainty in future temperature to 2.7°C – 2.9°C (Fig. 3). The historical constraints had different impacts on the sampled aerosol uncertainty scalers. All of the sampled OC scalers passed through the historical constraints (Fig. 4b), while the constraints had a modest effect on the OC, BC, and SO_2d scalers (Fig. 4a, b, and c).

The historical constraints have the most noticeable effect on the SO2i uncertainty scalers. This is because of the large absolute magnitude of the uncertainty in aerosol indirect effects (Myhre et al., 2013), which results in a large role for assumptions about the strength of aerosol indirect cooling (Tomassini et al 2007, Meinshausen et al. 2009). This shows that strong (negative) aerosol indirect forcing is consistent with only a few numerical combinations of forcing values from other species, at least for default Hector climate system parameters. The sample analysis using HIRM illustrates how this modeling framework can be utilized to calculate the range of past and future temperature changes under assumed uncertainty in aerosol radiative forcing.

4.2 HIRM as a Tool for Development Case Study

Radiative forcing effects from aerosols are complex (Fan et al. 2016, Bond et al. 2013), and while the physics driving these complexities have been incorporated into ESMs, they are not considered in most SCMs. For example, consider black carbon (BC): unlike cooling effects from aerosols that scatter shortwave radiation back into space, BC heats within the atmosphere, and also at the surface when deposited on snow or ice, potentially contributing to both cloud indirect cooling and heating effects (Bond et al. 2013). It can also increase cloud amounts, as BC atmospheric heating stabilizes the atmospheric thermal profile (Bond et al. 2013). Experiments conducted with ESMs have found large differences in the response to a step change in BC emissions compared to a step change in CO_2 (Sand et al. 2015; Yang et al. 2019).

Incorporating these dynamics into Hector would be a nontrivial task, but HIRM can be used to estimate what effect they would have on the model's global temperature. For this case study, HIRM was set up to emulate Hector RCP 4.5 as before, but with one difference: instead of pairing the BC RCP 4.5 RF time series with Hector's single IRF, the BC RCP 4.5 RF time series was paired with a BC-specific IRF. Since HIRM is set up with a BC-specific IRF, the results will no longer be equivalent to Hector's. Instead, the results illustrate what Hector's temperature could be if the BC dynamics were modified.

The BC-specific IRF was derived using output from a study that performed BC emission step tests with the ESM NorESM-1 (Sand et al. 2015). Mathematically, the derivative of a step response is equal to the impulse response function, and therefore we can derive an impulse response function from the step response results reported in the Sand et al. ESM experiment. The

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temperature response to a BC step in ESM experiments is well fit by a single exponential approach to a constant response (see Yang et al. 2019 for details). We fit the Sand et al. (2015) abrupt BC step response as:

$$T(t) = A\,(1 - e^{\frac{-t}{\tau}}), \tag{5}$$

The results of a nonlinear optimization of this function returned values of and τ that were 1.8 °C and 2.1 years, respectively. These optimal values were used in Eq. (6), the differentiated form of Eq. (5), to provide a numerical BC temperature impulse response function corresponding to the Sand et al. (2015) result:

$$\mathrm{R_t}(t) = \frac{\mathrm{A}}{\tau}\, \mathrm{e}^{\frac{-y}{\tau}} \mathrm{dt}, \tag{6}$$

The numerical result of Eq. (6) is converted to a BC impulse response per unit forcing by dividing by the forcing from a 133 Tg BC emissions change (used in Sand et al. 2015) using Hector's default forcing per unit BC emission assumptions. With this transformation we have replaced Hectors' default BC representation in HIRM with the Sand et al. temperature response in both magnitude and temporal behavior.

We found that the BC Sand et al. IRF has a weaker temperature response in the perturbation year and a more rapid decline in temperature response compared to Hector's global IRF (Fig. 5a). The maximum IRF response for the BC Sand et al. IRF is 0.06 (°C W^{-1}m^{-2}) which is 0.03 (°C W^{-1}m^{-2}) cooler than Hector's IRF. In addition, the BC. Sand et al. IRF approaches 0 (°C W^{-1}m^{-2}) faster than Hector's IRF. These differences are expected since the BC Sand et al. IRF was derived from the NorESM-1 ESM, meaning that this IRF incorporates the complex cooling and warming effects of BC emissions, the net warming over land as compared to no net warming over oceans (Sand et al. 2015). When HIRM was configured with the BC Sand et al. (2015) IRF the global temperature was lower by 0.2 °C from 1750 to 2100 under the RCP 4.5 scenario (Fig. 5b). Based on these results, if Hector were modified to emulate this BC response, we predict that the model's global temperature would be cooler by approximately 0.2 °C in 2100.

We note the idea of different forcing agents has been around for quite some time. For example, this has been incorporated mechanistically for aerosols in the MAGICC model for around 30 years now (Wigley and Raper 1992), and more recently inferred by Shindell (2014) from GCM results. Richardson et al. (2019) used separate response functions for CO2, CH4, solar insolation, and aerosols, although the differences in these response functions were not discussed. As further information on species-specific IRFs become available it will be important to quantify the consequences of these different IRFs using tools such as HIRM.

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5 Discussion and Conclusion

In this paper we document and test HIRM, a framework that leverages the nonlinear dynamics of process-based SCMs within a computationally efficient, highly idealized linear impulse response model. Our two case studies demonstrate that HIRM can be used as a testbed to quickly examine the consequences of different model assumptions, and to estimate changes in parent model behavior from including new mechanisms. While other IRF-based models have incorporated nonlinear dynamics using a number of approaches (Hooß et al. 2001, Millar et al. 2017, ADD), HIRM is able to demonstrate nonlinear dynamics through its use of exogenous forcing inputs from Hector. HIRM is available as an open source R package (available at https://github.com/JGCRI/HIRM), its computational flexibility and short run time make it particularly appropriate for uncertainty analyses and experimental SCM design.

We demonstrated that HIRM can be used to examine uncertainty within the climate system, and that incorporating a more realistic BC temperature response into Hector has a significant impact on Hector's global temperature. If more studies corroborate the findings of Sand et al. (2015) and Yang et al. (2019) by observing shorter timescale responses for BC temperature dynamics across a number of ESMs and Atmosphere-Ocean General Circulation Models (AOGCMs), then SCM modeling groups will need to consider incorporating the BC temperature response dynamics into SCMs. Some SCMs, such as MAGICC 5.3 and MAGICC 6 (Wigely et al. 2002), already exhibit multiple temperate responses; interestingly, MAGICC has a shorter timescale for the temperature response for aerosols (Schwarber et al. 2019), but the resulting response in MAGICC still has a longer timescale than that from the AOGCMs (Sand et al. 2015, Yang et al. 2019).

During the HIRM validation experiments we demonstrate that most of nonlinearities are in the emissions to forcing steps, in which the SCM calculates concentrations from emissions and radiative forcings from concentrations, relationships that widely used (Etminan et al. 2016). In comparison the non-linearites in going from forcing to global-mean temperature are relatively minor in contrast. This implies that efforts to improve the representation of nonlinear behavior in SCMs should be focused on emissions-to-forcing processes. We note that we draw this conclusion by calibrating HIRM to a single process-based SCM; this finding should be verified using other models, including Earth System Models of Intermediate Complexity (Claussen et al. 2002). Such EMICs have more physically-based parameterizations but low levels of internal model noise, which would be valuable for exploring the magnitude and nature of non-linearites in going from forcing to temperature. If this finding holds for a wider class of models, this would mean that a wide range of model responses to forcing could be quickly simulated using IRFs. Good et al. 2013 showed that SCMs based on step responses work fairly well for more reproducing General Circulation Model (GCM) results suggesting that the assumptions underlying HIRM are valid.

The case studies showcase HIRM's flexibility, which is based on HIRM's dependence on a parent model. Arguably this can be viewed as a limitation or a tradeoff allows HIRM to be used as a tool for rapid exploration. One limitation of this framework

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is that interactions between forcing agents are not directly considered. For example, multiple species of aerosols may contribute to cloud indirect cooling effects. These interactions, however, are not well constrained (Fan et al. 2016) and, for many purposes where SCMs might be applicable, it is most important to be able to represent the overall (large) uncertainty range, rather than interactions among species that have yet to be definitively quantified. An effort to represent aerosol indirect effects semi-analytically (Ghan et al. 2013) demonstrated not only the multiple processes that are relevant but also the difficulty in understanding the drivers of the different forcing estimates from more complex models.

Insights gained from HIRM could be useful in future work applying impulse response functions in general and the design of simple climate models in particular. We suggest that improvements to simple climate models should focus on improving the representation of emission to concentration and concentration to forcing relationships. As we note above, however, it would be useful to also design comparisons with more complex models, perhaps EMICS given their lower noise and computational requirements, to determine the extent to which the temperature response to forcing in more complex models can be accurately represented by impulse response functions, particularly on 20-30 year time scales where GCM outputs are particularly noisy.

HIRM could also be used with data generated by other SCMs. This could be a useful way of decomposing differences in responses between SCMs (e.g. Nicholls et al. 2020) into differences in the emissions to forcing step compared to differences in the model's response to a forcing impulse. Similarly, HIRM could be used to examine the uncertainty due to the different forcing to temperature responses amongst SCMs (see Schwarber et al 2019 for examples of different forcing to temperature IRFs).

HIRM can be used as a testbed for future SCM development. As demonstrated here, the incorporation of a GCM-derived temperature response function for black carbon emissions results in a significantly different global mean temperature response (Figure 5). Exploration of the potential impact of such changes can be done quickly in HIRM to decide if changes should be incorporated into, for example, Hector. Incorporating such a change into the Hector model itself would be a more time and labor intensive process for several reasons. First, to incorporate this change into Hector one would need to decide how to physically interpret the faster BC response time seen in GCMs since Hector does not use impulse response functions directly. There is some debate if this is due to different response over land vs ocean, or if this is more closely related to differing hemispheric responses (Meinshausen et al. 2011, Shindell 2014, Sand et al. 2015). Further, explorations or model extensions using HIRM can be accomplished without a user having to understand Hector's code, dependencies, and coding standards.

Finally, this framework could also be used for analysis that requires capabilities not present in SCMs–for example, regional analysis. Regional temperature trends could be simulated by HIRM by incorporating the ratio of regional to global temperature responses for each forcing agent into HIRM (Sand et al. 2019 and Shindell and Faluvegi et al. 2009). This could be particularly valuable for a region such as the Arctic, where a variety of forcing agents, from regional sulfate (Acosta Navarro et al. 2016), local black carbon (Sand et al. 2013 and Yang et al. 2019), and global forcing changes, e.g. Arctic amplification, all may play

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While impulse response functions have been used widely in the scientific community, they have well-known limitations. At least in the context of the SCM used here, we demonstrate that the use of a forcing-based impulse response function overcomes most of these limitations. This insight should

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a role. This type of analysis could readily be accomplished using HIRM, including the wide range of uncertainty space that should be examined (e.g. Figure 3). Future research with HIRM could test IRFs set up with different climate sensitivity values and inputs from other process-based models.

Code availability

The HIRM R package is available at https://github.com/JGCRI/HIRM with an online manual available at https://jgcri.github.io/HIRM/ . The package is also archived on Zenodo (https://doi.org/10.5281/zenodo.3756122). Code and results related to the discussion and conclusions of this paper are available on the Open Science Framework (OSF) at https://osf.io/kmrj8/.

Author contributions

S. Smith conceptualized the Hybrid Impulse Response Model (HIRM). K. Dorheim and B. P. Bond-Lamberty developed the project software. K. Dorheim wrote the manuscript with contributions from all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

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RF agent	Min. 2011 RF	Max. 2011 RF	Hector Default 2011 RF
BC	0.05	0.87	0.40
OC	-0.21	-0.04	-0.17
SO_2i	-1.2	0	-0.60
SO_2d	-0.6	-0.2	-0.35

Table 1: The minimum and maximum 2011 radiative forcing values from IPCC AR5 8.SM table 5 (Myhre et al. 2013). These values were used to obtain the min and max aerosol uncertainty scalers for four RF agents (BC, OC, SO_2i, and SO_2d). Along with the 2011 RF of the default configuration of HIRM/Hector for RCP 4.5.

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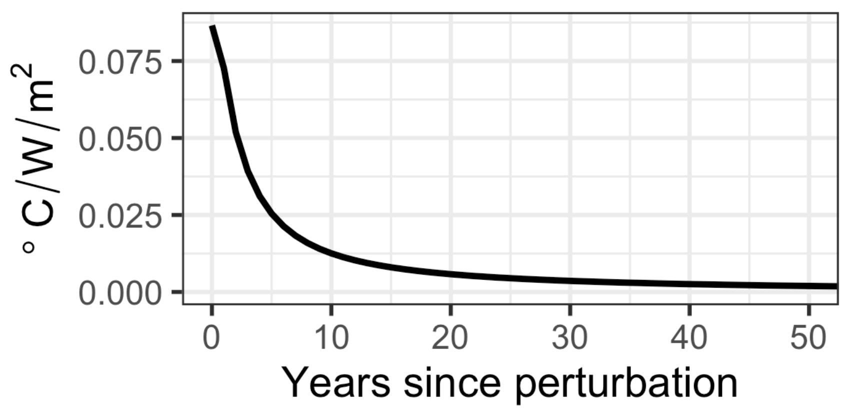

Figure 1: The first 50 years of the global temperature response to a radiative forcing perturbation for Hector v2.0; the remaining 2,500 years of the impulse response are almost constant and slowly approach zero. Here the black carbon emissions were doubled in 2010 relative to the Representative Concentration Pathway 4.5 value.

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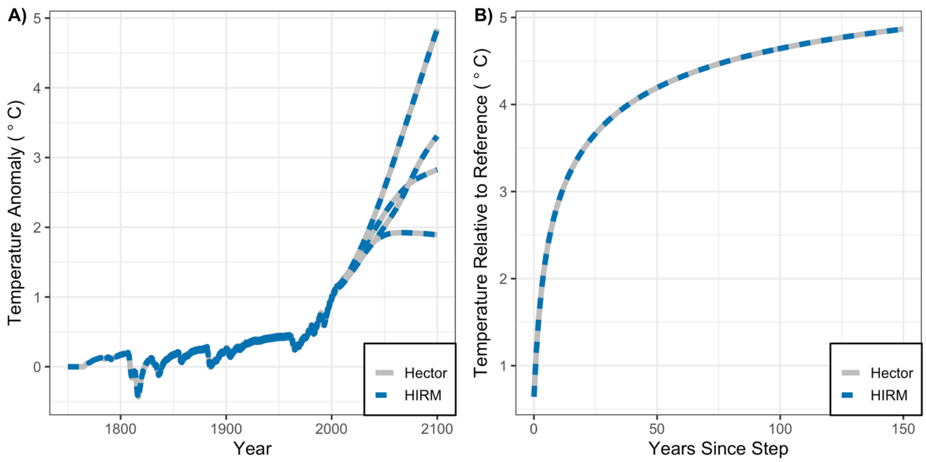
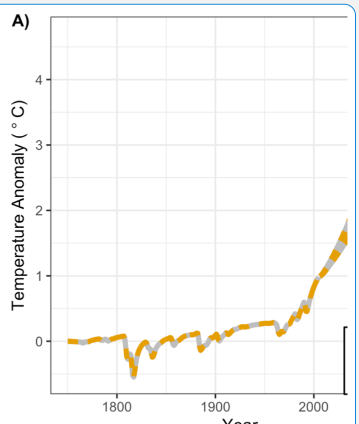


Figure 2: Comparison of Hector (grey dashed) and HIRM (blue dashed) global mean temperature anomaly from the two validation experiments. In panel (A) HIRM was used to the recreate Hector temperature for the four RCPs. The four lines in panel (A) from lowest to highest 2100 temperature represent results for RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5. Panel (B) compares the temperature response of HIRM and Hector from the abrupt four times CO_2 concentration step validation test.



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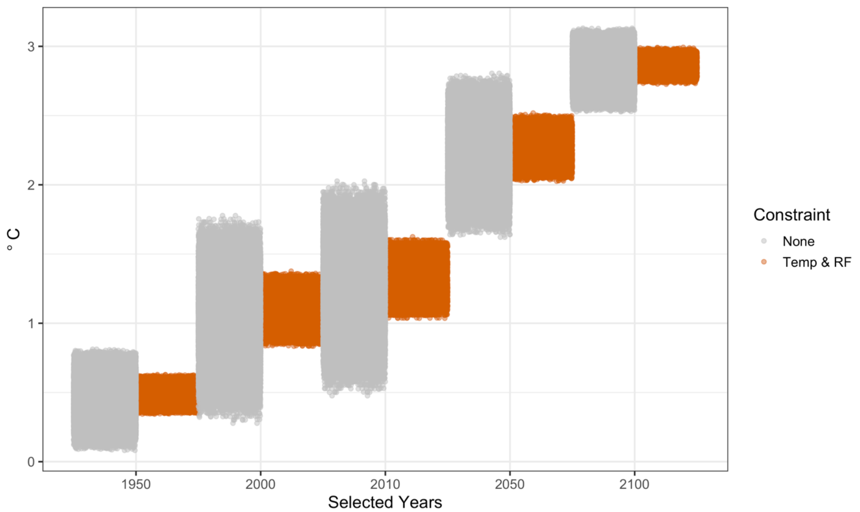

Figure 3: The temperature (°C)_spread from the aerosol uncertainty runs in selected years. The grey regions show all of the possible runs before the historical constraints were put into the place; orange regions are the runs that passed through both historical temperature and radiative forcing constraints. The uncertainty in temperature due to uncertainty in aerosol forcing decreases by 2100 because emissions of aerosols and precursor compounds decrease over time so their influence on temperature decays over time as well. We note that uncertainty in other climate system parameters, such as climate sensitivity and ocean heat diffusivity, were not samples in this application. Including these uncertainties would alter these results. Note that temperature change in 2020 is larger than the applied historical constraint ([0.65 to 1.1] °C over 1880–2012) because temperatures in this figure are relative to 1750.

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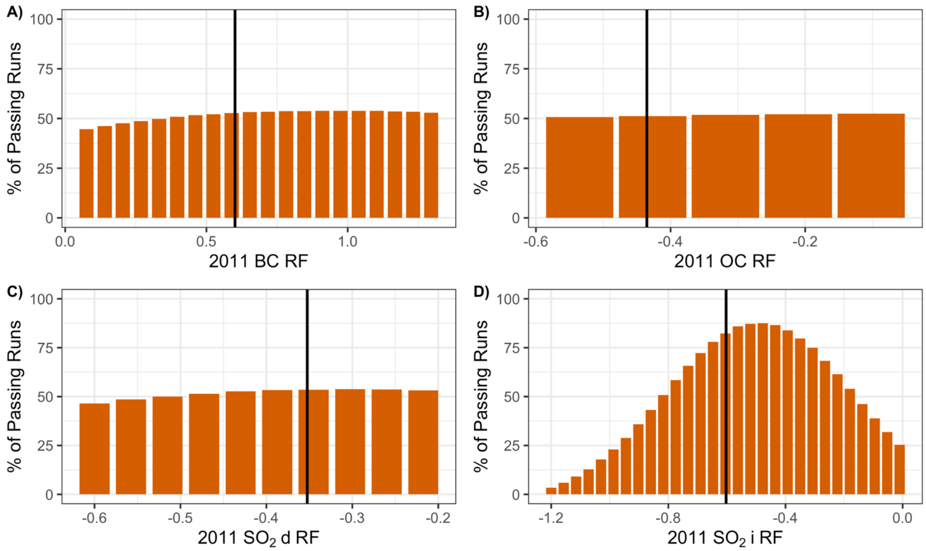
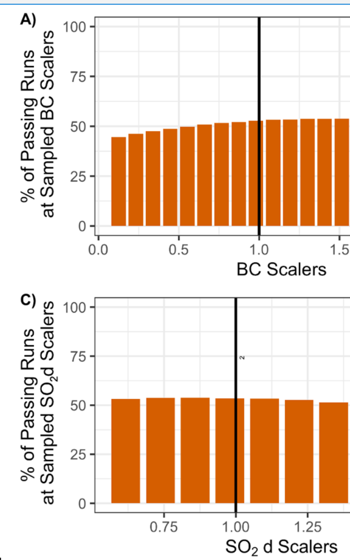


Figure 4: Uncertainty scalers used to vary (A) black carbon, (B) organic carbon, (C) direct SO_2 effects, and (D) indirect SO_2 effects aerosol RF time series in the uncertainty analysis. HIRM was run a total of 29000 times with every combination of uncertainty scaler represented on the x-axes of panels A-D, creating an ensemble of uncertainty runs with scalars varying for all radiative forcing agents. Each panel of this figure plots a projection of the percent of runs passing through the historical constraints as the 2011 radiative forcing agent of an agent is varied. The black vertical line marks default 2011 RF.



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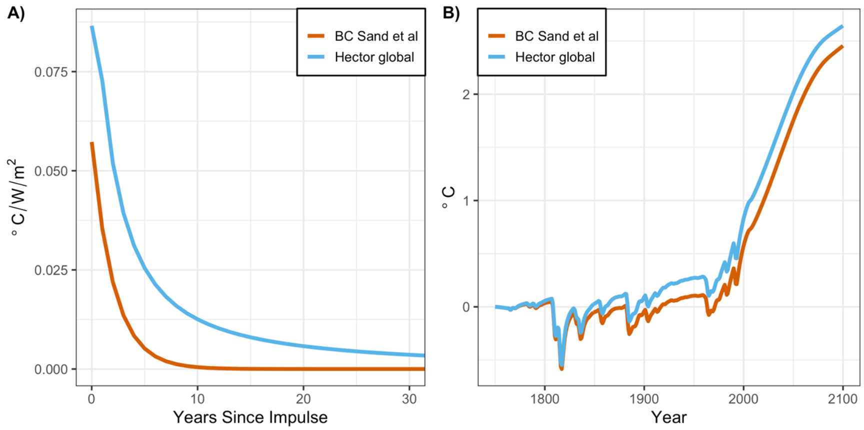

Figure 5: (A) Hector's IRF (blue) compared with the BC Sand et al. 2015 IRF (red). (B) HIRM total temperature for the Representative Concentration Pathway 4.5 for two HIRM cases, one that only uses Hector's IRF (blue) and the other pairing the BC RF time series with the BC Sand et al. 2015 IRF (red).

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Response to Referees
gmd-2020-33
Reviewer comments in normal type face. **Response in bold.**

Ben Kravitz (Referee #1)

The authors present a really interesting approach to simple climate modeling that I hadn't considered before. I think this is a smart idea. The authors have done a thorough job with their analysis. My only comments are related to phrasing and context of the results. I am recommending minor revisions.

Thank you for taking the time to review this manuscript. We believe that our changes address the issues raised in your review.

Lines 12-14: This sentence caught my attention as needing more caveating. In linear time-invariant systems the impulse response fully characterizes system dynamics. In nonlinear systems it doesn't. So as written, this sentence is coming across as though your fundamental methodology is flawed (which I'm sure it's not – based on my reading of lines 51-52, you do understand the distinction). I do agree that your approach captures _some_ of the dynamics, perhaps even the most important parts of it, depending on what dynamics your model is designed to represent. Some rephrasing is needed.

We have revised this sentence to read:
This structure allows it to capture the most crucial nonlinear dynamics encountered in going from greenhouse gas emissions to atmospheric concentration to radiative forcing.

Lines 32-34: That's one way to do it. There are others, for example:
https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2011GL048623

Thank you for bringing this publication to our attention. This is an interesting analysis in frequency space, but we're not sure how this would be translated into the applications to which SCMs are commonly applied, such as scenario analysis. We changed the text to clarify there are multiple ways to approach idealized simple climate modeling, see paragraph starting at line 33.

Line 39: I'd be careful with the word "nonlinearities". You can have linear feedbacks that still result in interesting dynamical behavior. I agree that chemistry can result in substantial nonlinearities (I think Kate Marvel had a paper on this looking at single forcings), and some GHGs are known to have a nonlinear relationship between concentration and forcing, but talking about the entire suite of carbon cycle feedbacks as nonlinear is perhaps too much.

Agreed, we adjusted the text in lines 47-51 to improve our discussion about how process based models incorporate complex climate interactions and nonlinear climate dynamics.

Lines 44-45: Again, they _can_ be. They don't have to be.

Good point. We borrow this terminology from Millar et al. 2017 and have adjusted the text starting in line 33 to better reflect this and caveat that there are multiple ways to use IRFs in simple climate modeling.

Lines 68-72: Clever. And an excellent description of where the potential problems lie. And I appreciate the validation of your assumptions later.

Thank you!

Lines 89-90: This assumption is known to be incorrect (i.e., efficacy; Hansen et al., 2005). That's not a problem for your analysis, but you'll need a caveat on your interpretation of your results.

Good point, this was not properly conveyed in the previous draft of the manuscript. We've added text in lines 86-88, and 106-109 to more clearly communicate this point.

Lines 96-97: This strikes me as appropriate. It's always tricky to delineate temperature from response because they coevolve, but your choice here makes sense.
Thank you.

Line 110: How do you impose the RF pulse in the model? (Or if this is described later, say so.)

The RF pulse is equal to the difference between the radiative forcing between the reference and the BC emission perturbation run. Text in lines 132 and 139 was modified to clarify this point.

Section 2.3 is a bit odd. I expected to actually see the results of the validation here. Perhaps move these short descriptions to more relevant points of the manuscript?

Section 2 and 3 were combined/reorganized so that the results of the validation tests were paired with the description of the test setup.

Lines 132-133: I'm having trouble understanding this sentence.

The sentence now reads "In this experiment HIRM was set up with the Hector derived IRF and a RF input from an abrupt four times CO2 concentration step".

Section 4.1: I'm having a bit of trouble understanding exactly what you did. If I understand it correctly, you (1) come up with ranges of uncertainties for each of those aerosol forcing terms, (2) sample those spaces to come up with 29,000 sets of parameters that you call uncertainty scalers, and (3) simulate those combinations in HIRM, throwing out results that don't match historical radiative forcing and temperature?

Yes, that is what we did. The wording in this section was changed to more clearly explain this case study, please see lines 192-227.

Line 214: Typo
Corrected.

Line 297: Typo in your acronym
Corrected.

Figure 2: Can you choose different colors? Orange and gray are difficult on the eyes.
We've selected another grey-color combination from a color-blind friendly color palette.

Kuno Strassmann (Referee #2)

Thank you for taking the time to review this manuscript. We value your feedback and believe that it has led to better, clearer version of the manuscript.

General comments

1. The manuscript describes the emulation of the temperature response to radiative forcing of a simple climate model with an impulse-response function. This is not a novel concept, and corresponds to what is typically one out of a set of many equations in existing simple climate models. The wording used by the authors suggests a more sophisticated, original approach, and is in my opinion a bit misleading. My main objection, however, is that the limitations of the model, which are quite strong, are not sufficiently addressed. The main limitation is that the (climate) model is not really coupled to a carbon cycle component and cannot therefore represent the carbon-cycle-climate feedback. Another important but never mentioned limitation is that the model presented has a fixed climate sensitivity. The approach could be extended by extracting IRFs from models (or model setups) with different sensitivities, but this is not straightforward.

We do believe that this is a new method to incorporate these dynamics into IRF based SCMs (we do not know of other modeling groups that do it this way) but by no means did we intend to suggest that this is the only way it has been done. We've expanded text in the introduction to make it clear to readers that there are several ways to approach this.

We've also added a new section 2.1 Parent Model Description (starting on line 66) to provide a clearer description of the connection between HIRM and Hector; we believe that this addresses your concerns related to the carbon cycle and limitations of the model. Model limitations are also discussed in lines (307-313).

Thank you for pointing out that HIRM could be configured with different climate sensitivities, that is a great idea and we have incorporated it as a future area of research in the discussion section (lines 344 - 346).

2. Furthermore, I find the validation exercises presented (section 2.3) not very informative, and I feel that the case studies (section 4) are only useful to demonstrate model application, and do not yield significant scientific insight. Several of the conclusions offered based on the latter appear unfounded.

We appreciate the Reviewer's point of view, but the case studies were chosen precisely to "demonstrate model application"--this is Geoscientific Model Development after all, a journal founded in recognition that model description papers are significant and necessary science. That said, we have made a number of modifications to section 4 that we feel have put into better context both of the validation and case studies.

3. Finally, the model description is incomplete, as no details on implementation are given, short of the model code itself. This said, the model as such seems to be correct, and my comments only concern its presentation, applications, and interpretation. I leave it to the editor to decide whether the limited material presented here warrants a publication in gmd.

Because Hector, the SCM model used here, is described in a number of previous publications, we have expanded short summary of its structure and capabilities and provide citations for readers interested in more detail (see section 2.1). This allows the current manuscript to focus on HIRM and its applications. With respect to HIRM itself, a new paragraph (lines 110 - 114) describes its structure and implementation details.

Specific comments

1. p1/25 Earth system models of intermediate complexity should be mentioned here, especially as they are referred to later in the paper.

EMICs have been incorporated into the manuscript starting in line 26.

2. p2/31 "SCMs can be characterized as either process-based or idealized climate models." All models, especially SCMs are idealized - a better word would be "abstract" as opposed to "process-based". However, it would be better to speak of IRF-based models, as the authors use the term "idealized SCM" synonymously, although other types of non-process-based models may exist.

This is an interesting point. We adopted this terminology from Millar et al. 2017 to be consistent with the language used by other simple climate modeling groups. This being said we hope the changes made to the introduction and in lines 35-39 address these concerns.

3. p2/40 Another key nonlinearity that should be mentioned here is the chemistry of CO_2 uptake at the ocean surface.

Thanks for this suggestion, as it is an important nonlinearity. We have added it to line 50.

4. p2/44 Are all idealized SCMs based on IRFs? It would be better (and avoid repetition) to say "IRFs used in SCMs are defined as. . .".

This sentence has been removed.

5. p2/48 AR5 mentions several types of IRF-model, but the main model used to calculate GWP represents the relationship between emissions and CO2, not temperature.

Thank you for pointing out the inaccuracy here. Due to changes in this section, this sentence has been removed.

6. p2/53 "ldealized SCMs may exhibit biased results, however, due to their lack of nonlinear dynamics." It is not in general true that idealized SCMs, meaning SCMs that are not (fully) process-based and use IRF functions, lack nonlinear dynamics. There are SCMs that apply IRFs only to the quasi-linear parts of the system, linking these with equations that capture essential nonlinearities (e.g. Joos and Bruno, 1996; Strassmann and Joos, 2018).

This was a miscommunication on our part; please see (lines 37-40) for the modified text which better situates HIRM among other nonlinear IRF based climate models. Thank you for sharing these references–they have been incorporated into the manuscript.

7. p2/56 Using the RF simulated by a model with nonlinearities as input hardly counts as "incorporating nonlinear dynamics".

We've tweaked the wording of the sentence so that now is reads: "In this manuscript we document and demonstrate a new highly idealized IRF-based framework".

8. p3/65 (whole paragraph) I find it rather misleading to call the use of an existing model to provide input a "framework", given that there does not seem to be any real coupling, i.e. exchange of information at intermediate timesteps. If this is the characteristic that distinguishes this "hybrid approach" from other IRF-based models, it does so in a negative way. There are SCMs that represent the climate response with IRFs and allow for coupling with a carbon cycle component at each timestep, for example, the BernSCM model (Strassmann and Joos, 2018). BernSCM combines IRF-based components describing linear systems with nonlinear parametrisations to capture the essential nonlinearities of the carbon cycle-climate system, and expresses the IRF-components as a system of ordinary differential equations to allow for efficient integration in coupled mode.

This paragraph has been edited to clarify how HIRM can be used with more sophisticated process-based models. However, we do feel that the term framework is sufficiently general to cover the application we have described here.

9. p3/69 “incorporate the nonlinear dynamics. . . if the majority of the nonlinear dynamics of SCMs occur between the emissions to radiative forcing calculation” -it would be more adequate here to say that the IRF-model, which really constitutes the contribution of the authors, does NOT incorporate any nonlinearities, because there aren’t any

Noted and this sentence has been removed as part of edits to clarify the presentation in response to referee comments. We aimed for the revised text to communicate that the non-linear dynamics are, indeed, incorporated only through the use of forcing time series from the parent SCM.

10. p4/96 (whole paragraph) It is true that the carbon-cycle-climate feedback could be included in the IRF. However, the resulting model would still have strong limitations. It is likely that such a model, being liearized, would give accurate results only for a limited range of forcing scenarios or time scales.

We agree, and mention this in the paper (see lines 123-129).

11. p4/114 “The end of the IRF was extrapolated with an exponential decay function” Please mention the decay timescale.

More details about the exponential decay have been added: line (143-144) now reads “This IRF had a length of 300 years, in order to ensure the IRF was long enough to be convolved with the RF inputs; the end of the IRF was extrapolated with an exponential decay function to a length of 3000 with a decay constant of 0.20”.

12. p4/120 “underlying assumptions about where the majority of the nonlinearities occur are true” - This simply means the climate component of Hector is linear, which is to be expected of an SCM and could be inferred by looking at the design of that model.

Hector incorporates a diffusive model for ocean heat uptake which is, by definition, non-linear. However, as we have shown here, this nonlinearity is relatively weak compared to the non-linearities in emissions -> forcing calculations.

13. p4/122 I don’t see what chemical processes could affect the relationship between RF and temperature, at least in an SCM.

We have revised the text in lines (154-156) to clarify. (Chemical processes can impact relationships between emissions and forcing.)

14. p5/126 “For each RCP. . .” this sentence is not very informative and could be dropped.

We believe that this text does provide important information about the validation test set up, however we have modified the text so that information is more clearly portrayed.

15. p5/149 As mentioned above, this finding is not surprising; it merely characterizes the Hector SCM and holds no scientific information on the physical climate as such.

This sentence is not intended to convey any information on the physical climate system but is intended to show the extent to which the HIRM emulation matches the original hector result. As noted above, such a good match is not a foregone conclusion.

16. p5/155 “difference of 0.0%” There are no significant digits in this number

Noted, please see line 172 where we have updated this to 0%,

17. p6/156 As for the additivity of temperature changes, the lack of nonlinearities in the Hector climate component is not a scientifically relevant finding.

As noted above, this is not a foregone conclusion.

18. p6/164 “In this analysis, however, the black carbon (BC), organic carbon (OC), indirect SO2 effects (SO2i), and direct SO2 effects (SO2d) RF input time series were varied.” It is not correct to only vary these components. The uncertainty of other forcings should also be considered. The uncertainty of CO2 RF, for example, though small in relative terms, is important due to the dominant contribution of that component. Leaving out these uncertainties will result in an overconstrained temperature range.

We certainly agree with the comments of the reviewer in terms of scientific principles. We note, however, that the purpose of this section is to demonstrate how the tool could be used (as part of the GMD model documentation paper), not to conduct a rigorous uncertainty analysis.

This has been noted in the modified text.

19. p6/169 “sampled at intervals of 0.04 W/m2” It should perhaps be mentioned that this sampling does not produce a plausible probabilistic distribution of the results, since the RF uncertainties cannot be assumed to be uniformly distributed. Since the authors do not make a probabilistic interpretation, this is not a major issue, however

Correct we do not produce probabilistic results and have added text in 1997 to explicitly state that this case study does not produce probabilistic results.

20. p7/189 “This shows. . .” due to the overconstraining mentioned, this result is not valid in my opinion. Consequently the exercise described is only useful as an illustration of using the model framework, as stated in the following sentence.

This is, indeed, an application of the model as noted. However, we disagree that this conclusion is not valid. We note that most historical aerosol forcing estimation experiments don't separately examine the effects of different aerosol components (e.g., Forest 2018) -

although Tomassini et al 2007 and Meinshausen et al. 2009 are exceptions and these citations have been added (although numerical values are not available making it difficult for us to compare directly). Most of these experiments generally scale total aerosol forcing up or down. In this exercise we have full forcing time series with different time paths for each forcing component (see Smith and Bond 2014 for examples). So we believe that our statement of what uncertainty components contribute to the constrained forcing range is valid as stated.

21. p7/193 (section 4.1) It is possible to use an IRF for a specific component from another model, as the authors do, but I am not sure how meaningful this is, since this mixes the climate responses of two different models. To get a consistent model emulation the IRFs for the other RF components should, in principle, be taken from the same model (i.e., NorESM-1).

We agree that a fully consistent emulation of any given climate model would entail consistent IRFs (and any other parameters) for all species - however there is little evidence that large-scale climate responses are related to aerosol forcing responses in models (e.g., aerosol forcing is not correlated with climate sensitivity in CMIP6 models - Smith et al. 2020 - https://doi.org/10.5194/acp-20-9591-2020) so the experiment we present is reasonable as a sensitivity exercise.

Given that two coupled models so far have shown a dramatically different shape for the BC impulse response, our goal is to examine the impact of changing the BC IRF on global temperature. We, therefore, wish to use a realistic BC impulse for this calculation as derived from NorESM instead of postulating something more hypothetical.

22. p8/239 "it demonstrates nonlinear dynamics" I find this claim unfounded since the nonlinearities in question concern the dynamics of a previously existing model, while the model component contributed by the authors cannot represent the relevant nonlinearity, i.e., that of the climate-carbon cycle feedback.

Correct, HIRM depends on the parent model–in this case Hector. This limitation has been added to the manuscript in lines 307. We have clarified the wording.

23. p9/253 (whole paragraph) "most of the linearities" - there is no finding about any specific nonlinearities, and the fact that the Hector SCM has a linear RF-temperature response is no basis for a recommendation for further model development. The nearlinear relationship between RF and temperature is well known and has been demonstrated and exploited in SCMs for a long time (e.g., Joos and Bruno, 1996).

This paragraph has been modified to reflect this comment.

24. p9/271 "we demonstrate that the use of a forcing-based impulse response function overcomes most of these limitations." I don't see that any limitations are overcome by this approach.

Noted, this text has been removed.

25. p9/273 “These findings imply. . .” Again, there is no basis for such a recommendation.

Noted, this text has been revised so as to clarify the implications of this work.

Technical corrections

- p5/132 “In this experiment HIRM was configured” - The word “was” seems to be superfluous here.
Removed.

- In Table 1, the unit should be given.
Added.

References

- Joos and Bruno, 1996. Pulse response functions are cost-efficient tools to model the link between carbon emissions, atmospheric CO2 and global warming, Phys. Chem. Earth, 21, 471–476.

- Strassmann, K. M. and Joos, F.: The Bern Simple Climate Model (BernSCM) v1.0: an extensible and fully documented open-source re-implementation of the Bern reduced form model for global carbon cycle–climate simulations, Geosci. Model Dev., 11, 1887– 1908, https://doi.org/10.5194/gmd-11-1887-2018, 2018

Thank you for including these references, very helpful.

Anonymous Referee #3

The authors present a model that couples radiative forcing (potentially from any source, but here solely from the Hector simple climate model) to an impulse response function to calculate global mean surface temperature anomaly, with the possibility to choose different impulse response functions for different forcings (e.g. black carbon).

It is difficult to see what kind of advance this model is. HIRM relies very heavily on Hector, the details of which are documented extensively elsewhere. Using different IRFs for different forcings is not a new concept either (e.g. Richardson et al 2019 for CO2, CH4, BC, SO2 and solar forcing, Larson and Portmann 2016 for volcanic as a special case).

Indeed, the idea that there is a different climate response depending on the forcing agent has been around for quite some time. For example this has been incorporated mechanistically for aerosols in the MAGICC model for around 30 years now (Wigley. and Raper 1992), and more recently inferred by Shindell (2014) from GCM results. We have expanded our text to add this context. We note that this is a model description paper; we are not claiming that our results are new scientific advances, but rather are presenting this

model as a useful tool for rapid analysis and as a testbed for model development and analysis. This is explicitly within scope of journals such as GMD.

This could be a nice module to include in Hector as an alternative way to calculate temperature in that model. The comparison to the default Hector temperature response function is shown in Figure 2 and seen to be almost identical, so this simplification (is it a simplification?) may be worthwhile. But, due to its nearly total dependence on Hector and the fact that species-dependent efficiacy response functions have been done previously, it doesn't qualify as a brand new model for me. Rather it is a submodule of Hector.

We have clarified in the revised text that HIRM is independent of Hector, it can be used with input from any model and with any IRF (lines 57-60). We use Hector because it is also open source (so the work here can be replicated by anyone who wishes to do so) and has a convenient interface for obtaining radiative forcing and temperature time series.

It is possible that there is more to this paper than meets the eye, but if there is it should stand out more, and if the authors believe this does warrant a standalone model, expend some effort in decoupling it from Hector and explain what is improved or new over e.g. Richardson et al. 2019

We hope the revised text does this. Note, however, that we do not claim that this work is improved over works such as Richardson et al. (2019), which presents an analysis of results from complex models (both coupled and atmosphere-only using a slab ocean). HIRM could certainly be used to quickly examine the implications of the IRFs derived in work such as Richardson et al., but that work is of a different nature than what we present here in a model description paper.

Specific comments:

Line 18: Examining the effect of aerosol forcing on global temperature: a worthwhile cause. There is not actually done in this paper however. To me this would involve varying the present-day forcing of aerosols, climate sensitivity, and carbon cycle feedbacks, and investigating how this would cause temperature to evolve in a probabilistic fashion. The projections shown in figure 3 are far too constrained as explained in a later comment.

We certainly agree with the comments of the reviewer in terms of scientific principles. We note, however, that the purpose of this section is to demonstrate how the tool could be used (as part of the GMD model documentation paper), not to conduct a rigorous uncertainty analysis.

Around line 25, there is a missing link between ESMs and SCMs: Earth System Models of Intermediate Complexity (EMICs). In fact, you could say that in decreasing order of complexity we have ESMs > GCMs > EMICs > SCMs.

EMICs have been incorporated into the manuscript starting in line 26.

In the paragraph starting on line 32, the authors discuss the differences between process-based and idealized simple climate models, presumably as a preface for introducing their own model that couples the two components. It is not clear to me that these two concepts are necessarily separate, and if they are, this model may not be as novel as the authors claim. The later versions of FAIR (Smith et al., 2018, GRL) include an impulse response function for CO2 emissions to concentrations and for converting forcing to temperature, and "processed-based" representations of concentrations of greenhouse gases, radiative forcing of GHGs and short-lived climate forcers, and feedbacks from temperature on the carbon cycle and radiative forcing. Leach et al. (2020) in the Generalised Impulse Response model extends the impulse-response framework of the carbon cycle to other greenhouse gases and short-lived climate forcers. In both of these models, the radiative forcing is internally calculated (process-based, in the language of the authors?) and not supplied externally/provided by a different model (as discussed in lines 82-83 for HIRM). For my benefit if not others, could you cite maybe one example of a "process-based" SCM on line 32 if these concepts are separate? MAGICC perhaps?

We have included MAGICC as an example of a process-based model in line 33. Furthermore the changes made to second and third paragraphs of the introduction section help clarifies the discussion regarding process based and impulse response function based models.

line 37: "top of troposphere" - this is an old and incomplete definition of radiative forcing, and effective radiative forcing is now preferred - the Smith et al (2018, JGR) reference which is in the bibliography (but not in the text, oddly) goes into some detail on this. I should say this discussion is of limited importance for SCMs.

We have expanded this discussion slightly to clarify how radiative forcing is defined in Hector (and, therefore, by inference in the examples given in this work).

line 54: "in addition, the physical interpretation of their behaviour is not always straightforward". Please explain why not.

This text was confusing and has been removed.

Line 90: This is a confusing paragraph. On first reading it seems like HIRM doesn't allow for species-dependent efficacy. Then I later read the discussion on BC, and see that the different IRF for BC can be included, which *is* a different efficacy (and time-dependent too). Then on second reading I see that the authors are talking about Hector not having species-dependent efficacy which is more evidence that this model is a component of Hector and not standalone. In general, in section 2.2 it is difficult to follow what the authors did. A flow diagram could help.

Yes, this section was unclear. HIRM can be configured with a unique IRF for each RF agent. However, for the purposes of the validation exercises HIRM had to be set up the same way as Hector, which only exhibits a single IRF. Text clarifying this point has been added in lines (86, 111, and 307).

Lines 97-102: It is not correct to exclude carbon cycle feedbacks. It is no good if HIRM can emulate Hector with feedbacks switched off if the latter is not representative of the real world. If the forcing comes from Hector in the first place, feedbacks need not be excluded in the Hector configuration, because HIRM doesn't calculate forcing. The analogy here would be concentration-driven GCM runs, where the concentrations are calculated by MAGICC (which includes carbon cycle feedbacks) but the GCMs themselves do not, going from concentrations > forcing > temperature.

We've modified the text from lines (123-129) where we discussed the decision to exclude the carbon cycle responses. For the purpose of our validation experiments it is appropriate to exclude them here, but they could be important to include in other applications.

line 120-121: people have underlying assumptions, but software doesn't

We respectfully disagree, but this is perhaps just an issue of semantics. Perhaps a better way of expressing it would be that programmers encode their assumptions into the software they create.

line 124: Hector's IRF - this is the function in figure 1 isn't it, because Hector is not impulse-response based. Could just refer to confirm.

Correct. Figure 1 is Hector's IRF that was obtained from by running hector as described in the text.

lines 131-132: it goes without saying that 4xCO2 tests the climate model's response to CO2. The importance of the 4xCO2 experiment is that it can be used to (imperfectly) estimate climate sensitivity, climate feedback and CO2 radiative forcing in GCMs (Gregory et al 2004) by using a forcing with a high enough signal-to-noise ratio to get a clear signal but still small enough to avoid substantial non-linearities and tipping points. Hence it can be used as a line of evidence for climate sensitivity, which itself is an input parameter to many simple climate models. Also, putting the Schwarber reference in line 132 reads like they invented this experiment.

Correct, it was not our attention to present the Schwarber reference like they invited this experiment, but we see how it could have been interpreted this way. We have modified the text to add more appropriate context.

line 145: The difference ... and the following sentence, can be dropped. It's apparent from the naked eye that the differences are imperceptible, I don't think this needs to be rigorous. Similar sentence in following paragraph.

Noted, text in this section has been changed.

line 157: Which SCM? Hector?

Noted and corrected.

lines 161-162: needs a reference

We now cite Forest 2018.

line 174: 29000 is a bit of a random number, is there a motivation for this?

29000 is the number of combinations of the uncertainty scalars when the uncertainty rangers were sampled, this is described in the text starting in line 203.

lines 176-177: wrong values (-1.9 to -0.1 is AR5 "very likely" i.e. 5-95% estimate), and also wrong citation (Myhre et al., 2013).

Correct, our range was modified from Myhre et al. 2013, the text in lines 212-213 more clearly describes the range that was used.

Figure 3: why does uncertainty reduce over time? 2100 temperature is very tightly constrained, but this is the timeframe over which uncertainties in radiative forcing, climate sensitivity and carbon cycle feedbacks multiply. I know these are not sampled, but this should very clearly be stated and the fact that this is not a true future uncertainty quantification of warming. I'd also check the constraints - is 1.6C of warming in 2010, which passes the constraint, realistic?

The uncertainty decreases by year 2100 because overall aerosol forcing decreases. In the scenario that was used aerosol and precursor emissions decrease substantially over the 20th century so that, regardless of what is assumed about forcing per unit aerosol/precursor emissions, the overall impact of aerosol forcing is smaller. Therefore, the absolute magnitude of the impact of aerosol forcing uncertainty in 2100 also decreases.

Thank you for the careful reading of the figure. The upper constrained value of around 1.6C in 2010 is consistent with the applied temperature constraint which is only over 1880–2012. There is a non-trivial amount of positive forcing prior to 1880 due to both well-mixed greenhouse gases and also, potentially, from aerosols (If BC forcing is strong and cooling aerosol forcing is weak). See Smith and Bond 2014, Figure 4. The figure caption has been amended to note this.

lines 189-190: Important point, long known. Compare/cite some relevant studies e.g. Forest (2018). Figure 4 would be more naturally expressed in terms of a W/m2 aerosol forcing posterior for e.g year 2010, perhaps add a subpanel e. This would back up the claim that strong aerosol forcing values do not pass the constraints.

Most of these previous studies do not represent uncertainty in the different aerosol components separately. Only Meinshausen et al. 2009 and Tomassini et al 2007 include BC, OC, SO2 direct, and aerosol indirect forcings (Forest 2018, Table S4), but only show them graphically; we have added those references. Note in this example application the aerosol

forcing range is supplied as a constraint so its not an independent output to compare to these previous results.

Figure 4 and its caption has been updated as per your suggestion.

Line 214: Mention the perturbation size from line 220 here. Richardson et al. (2019) included a multi-model response for BC and would be more appropriate to use than the single-model study here.

We agree this would be useful to use the Richardson et al response function. However, the parameters of their multi-model response function for BC was not provided in their paper or SI (and is not yet available from the authors). The perturbation size is mentioned in line 262.

line 230: maybe a better wording would be "... the global temperature was 0.2C lower using the specific BC IRF from Sand et al. (2015)." Avoid using "decreased" in this sentence.

Noted and changed.

minor:

line 9: Earth (rather than earth)
line 29-30: would probably get picked up in proofing but check citation spellings (Meehl, Meinshausen)
line 40: Myhre et al.
line 91: forging
Noted and changed.

line 200: also Richardson et al. 2019
Added.

line 226: units, should be C/(W/m2)? i.e. the m2 is in the numerator

It now reads °C $W^{-1}m^{-2}$

line 253: HRIM (and in several other places)
line 244: "a" not required

Noted and changed.

line 245: "dynamics" - not really dynamics is it - just a different IRF

Noted, this text changed to "temperature response".

line 438: 29000 times

Noted and changed.

References:

Richardson et al. 2019: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019JD030581
Larson and Portmann 2016:
https://journals.ametsoc.org/jcli/article/29/4/1497/35504/ATemporal-Kernel-Method-to-Compute-Effective
Smith et al. 2018, GRL: https://gmd.copernicus.org/articles/11/2273/2018/
Leach et al. 2020: https://gmd.copernicus.org/preprints/gmd-2019-379/
Forster et al. 2016: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016JD025320
Smith et al. 2018, JGR: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2018GL079826
Gregory et al. 2004: https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2003GL018747
Forest 2018: https://link.springer.com/article/10.1007/s40641-018-0085-2

Thank you for the suggested references.