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Improving reduced complexity model assessment and usability

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Abstract

Reduced complexity climate models are useful tools with practical policy applications, yet evaluation of their performance and application is nascent. We call for stakeholder-driven development and assessment to address user needs, including provision of open-source code and guidance to inform model selection and application.

The climate community uses computational models to project climate change¹, but no single model is suited for every situation. A variety of models provides an important diversity of options (Table 1), from comprehensive, high-resolution Earth system models (ESMs) to a simple set of equations that transforms emissions into temperature pathways based on impulse-response functions. In this Comment, we focus on reduced complexity (RC) models, which range from idealized, function-based models that only project global mean temperatures to process-driven models that project multiple variables with regional resolution.

Choosing the right RC model

Three technical characteristics of RC models make them preferable to complex atmosphere–ocean general circulation models (AOGCMs) for certain applications: (1) computational efficiency, (2) adjustable model parameters and (3) lack of chaotic behaviour (Box 1). Beyond these common characteristics, RC models are diverse: they may include additional end points (such as sea-level rise), geographic resolution or key feedbacks (like permafrost thaw).

Beyond their technical characteristics, RC models have key administrative characteristics² such as whether the code is open source, if user guides exist, simplicity of the model structure, user-friendliness or computational platform requirements. Relevant administrative or technical characteristics will depend on the application for which the RC model is being used, and the circumstances of the user (Table 2).

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Competing interests

The authors declare no competing interests.

In an assessment of climate change damages valuation, the U.S. National Academy of Sciences (NAS) provided criteria on the use of RC models that are likely to be pertinent for RC model applications outside of valuation. These criteria include: consistency with scientific understanding of equilibrium climate sensitivity, transient climate sensitivity and transient sensitivity to emissions; emissions pulse adjustment timescales; transparency and simplicity; incorporation of non-carbon dioxide forcings; ability to turn individual components (such as carbon cycle feedbacks) on and off for testing; the inclusion of additional climate end points, such as sea-level rise and ocean acidification; and the capacity to perform uncertainty propagation³.

Higher-complexity RC models better capture some climate characteristics. For example, short-lived aerosol impacts differ from those of well-mixed greenhouse gases because aerosol forcing is predominantly over Northern Hemisphere land masses, suggesting that models permit hemispheric and land/ocean differentiation⁴. The Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC) has these characteristics⁵, but many RC models do not. Similarly, the adjustment timescale to emissions differs between black carbon and greenhouse gases^{6,7}, and multi-century projections require a dynamic ocean to model heat uptake (and sea-level rise) over long timescales⁸.

On the other hand, developing global warming potential estimates is an application that may suffer from increased complexity. While the inclusion of climate-carbon feedbacks in the calculation of global warming potential may be scientifically more accurate, the increased complexity of this calculation and the resulting reduced transparency has been shown to outweigh the improvement (on the order of 2%) in the final values⁹. Generally, for public policy applications, there are trade-offs between simplicity and improved representation of the climate system.

Objectives of RC model assessment

The Reduced Complexity Model Intercomparison Project (RCMIP) is an international effort outside the official Coupled Model Intercomparison Project (CMIP) process, with 15 RC models participating to date¹⁰. This project builds on prior work comparing a limited number of RC models against each other: AOGCMs, ESMs and Earth system models of intermediate complexity (EMICs)^{9,11–13}. RCMIP partially fills a “substantial knowledge gap”¹⁴ by evaluating a broad range of models using emissions- and concentration-driven historical and future scenarios, and by testing their ability to emulate CMIP6 ESMs across dozens to hundreds of output variables. While RCMIP is an important and ongoing process, there is still a need for assessments beyond this first stage of self-evaluation by the RC model community, with the following concrete objectives.

Identify transparent and open-source code.

Online repositories facilitate transparency and sharing of open-source code. For example, the GitHub repository used by the Hector model (www.github.com/JGCRI/hector)¹⁵ allows the user community to engage in model development, provides access to previous model releases and offers branches of the code that include modules and capabilities that are not part of the main model. Other relevant administrative characteristics considered by

Thompson² include ease of updating, clear licensing, widely used model platforms and existence of stable funding for the model developers.

Facilitate user-driven guidance.

The differences among RC models need to be better understood and communicated. Stakeholder engagement could guide the development of user-friendly documentation to better understand the differences among RC models (including differences in which Earth system processes are included, which parameters are tuneable and how uncertainty is characterized within the model). For example, some RC models may capture more complex interactions but at the cost of much larger code bases (like MAGICC and Hector), resulting in increased challenges for the interpretation of results. The trade-off between fidelity and simplicity is another administrative characteristic that can benefit from stakeholder input, as the model development community may be more accepting of complexity than many RC model end users.

Hone application of multiple models.

The use of multiple models permits exploring structural uncertainties, and should be encouraged. As an example, the recent Intergovernmental Panel on Climate Change (IPCC) assessment¹⁴ used the Finite Amplitude Impulse Response (FaIR) model and MAGICC to provide more confidence in its findings. However, as a contrast, the same assessment also used eight different observational and reanalysis datasets for historical temperatures and 24 CMIP5 models for climate projections, raising the question of how many RC models can be used before reaching the point of diminishing returns. The appropriate number may well be greater than two, though consideration of parametric uncertainty can compensate.

Gauge parameter ranges.

In the *Valuing Climate Damages* assessment³, NAS discussed the development of appropriate ranges for key input parameters. If a parameter is well characterized and has consistent interpretations between models, such as equilibrium climate sensitivity, the parameter ranges can originate from assessments, such as those from IPCC. Other parameters may be idiosyncratic to a single model. One approach to gauge parameter ranges is to calibrate them based on observations^{16–18}. Recommendations regarding parameter choice, coupled to similar work from the integrated assessment model (IAM) community, could inform uncertainty analysis at each stage of the modelling process, from emissions scenario assumptions through to climate impacts.

Standardize nomenclature.

RC models are also referred to as ‘RCMs’ or ‘simple climate models’; however, RCM is an acronym also used for regional climate models, and ‘simple’ is pejorative and not necessarily accurate. An assessment could address this nomenclature issue along with whether distinguishing impulse response models from energy balance models adds any value.

Benefits of stakeholder involvement

Multiple avenues provide stakeholder-driven assessment and guidance. First, assessments could be specific to particular users and tasks, or overview the most common RC model applications and users. RCMIP or other efforts could facilitate this by considering model recommendations for specific uses, input parameter guidance and explanations of differences between models while reaching out beyond model developers to include stakeholder groups. The NAS assessment³ exemplifies how experts can provide recommendations and criteria for an RC model's application. These criteria could be assessed across several RC models to provide a framework for future evaluations².

Second, individual government bodies or organizations could perform their own evaluations guided by their own requirements. In addition, there should be outreach to and/or inclusion of appropriate stakeholder communities to assess their user needs. Such assessments may need to be updated as models develop and their applications and user needs evolve. While these assessments could be ad hoc, a more structured approach, like a standing stakeholder workgroup, would incentivize standardized output and documentation, thereby smoothing the process.

One challenge that arises is that investment in stakeholder assessment and engagement can carry opportunity costs. While increased model adoption by stakeholders is one benefit of interacting with assessment processes, organizations could also incentivize RC model developers with funding. Encouraging open-source code and documentation would also allow external bodies to assess the models independently, reducing the burden on developers. Alternatively, the standardized set of outputs developed by RCMIP could be aggregated, compared and visualized in a central repository, taking lessons from the IAMC Scenario Explorer¹⁹ and the pyam package²⁰.

Steps forward

The growing use of RC models will benefit from a structured and independent assessment. This would reveal their relative strengths and weaknesses, and identify which models are superior for specific purposes. Such assessments, by a reputable organization, should incorporate stakeholder input to identify relevant user needs and applications. The output would inform policymakers, researchers, nongovernmental organizations, industry groups and the public on the application of models to critical policy issues.

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References

1. IPCC Climate Change 2013: The Physical Science Basis (eds Stocker TF et al.) (Cambridge Univ. Press, 2013).
2. Thompson TM WIREs Clim. Change 9, e532 (2018).

3. National Academies of Sciences, Engineering, and Medicine. Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide (The National Academies Press, 2017).
4. Shindell DT *Nat. Clim. Change* 4, 274–277 (2014).
5. Smith SJ, Wigley TML, Meinshausen M & Rogelj J *Nat. Clim. Change* 4, 741–742 (2014).
6. Sand M et al. *Nat. Clim. Change* 6, 286–289 (2016).
7. Stjern CW et al. *J. Geophys. Res. Atmos* 122, 11462–11481 (2017). [PubMed: 32441705]
8. Nauels A, Meinshausen M, Mengel M, Lorbacher K & Wigley TML *Geosci. Model Dev* 10, 2495–2524 (2017).
9. Millar RJ, Nicholls ZR, Friedlingstein P & Allen MR *Atmos. Chem. Phys* 17, 7213–7228 (2017).
10. Nicholls ZRJ et al. *Geosci. Model Dev* 13, 5175–5190 (2020).
11. Joos F et al. *Atmos. Chem. Phys* 13, 2793–2825 (2013).
12. van Vuuren DP et al. *Climatic Change* 104, 255–285 (2011).
13. Schwarber AK, Smith SJ, Hartin CA, Vega-Westhoff BA & Sriver R *Earth Syst. Dyn* 10, 729–739 (2019).
14. IPCC Special Report on Global Warming of 1.5 °C (eds Masson-Delmotte V et al.) (WMO, 2018).
15. Hartin CA, Patel P, Schwarber A, Link RP & Bond-Lamberty BP *Geosci. Model Dev* 8, 939–955 (2015).
16. Meinshausen M et al. *Nature* 458, 1158–1162 (2009). [PubMed: 19407799]
17. Goodwin P *Clim. Dyn* 47, 2219–2233 (2016).
18. Libardoni AG, Forest CE, Sokolov AP & Monier E *Adv. Stat. Climatol. Meteorol. Oceanogr* 4, 19–36 (2018).
19. Huppmann D et al. IAMC 1.5°C Scenario Explorer and Data hosted by IIASA (IIASA and IAMC, 2019).
20. Gidden MJ & Huppmann D J. *Open Source Softw* 4, 1095 (2019).
21. Collins M et al. in *IPCC Climate Change 2013: The Physical Science Basis* (eds Stocker TF et al.) 1029–1136 (Cambridge Univ. Press, 2013).
22. Smith CJ et al. *Geosci. Model Dev* 11, 2273–2297 (2018).
23. Deser C, Phillips A, Bourdette V & Teng H *Clim. Dyn* 38, 527–546 (2012).
24. Meinshausen M, Raper SCB & Wigley TML *Atmos. Chem. Phys* 11, 1417–1456 (2011).
25. Hulme M, Raper SC & Wigley TM *Energ. Policy* 23, 347–355 (1995).
26. Final Rule for Model Year 2012 – 2016 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards (US EPA, 2016); <https://www.epa.gov/regulations-emissions-vehicles-and-engines/final-rule-model-year-2012-2016-light-duty-vehicle>
27. Palmer MD, Harris GR & Gregory JM *Environ. Res. Lett* 13, 084003 (2018).
28. Rogelj J et al. *Nat. Clim. Change* 6, 245–252 (2016).
29. Meinshausen M et al. *Climatic Change* 109, 213 (2011).
30. Soldatenko S & Colman R *Tellus A* 71, 1554421 (2019).
31. Lewis N & Curry JA *Clim. Dyn* 45, 1009–1023 (2015).
32. Rogelj J, Meinshausen M & Knutti R *Nat. Clim. Change* 2, 248–253 (2012).
33. Fawcett AA et al. *Science* 350, 1168–1169 (2015). [PubMed: 26612835]
34. Riahi K et al. *Glob. Environ. Change* 42, 153–168 (2017).
35. Nordhaus W *Am. Econ. J. Econ. Policy* 10, 333–360 (2018).
36. Michaelis P & Wirths H *Environ. Econ. Policy Stud* 22, 555–584 (2020).

Box 1 |**Technical benefits and applications of RC models****Computational efficiency**

Computational efficiency is typically the most important reason for using RC models rather than more complex AOGCMs, ESMs or EMICs. RC models generally produce results in seconds or less compared to the thousands of hours of processor time for each year simulated in AOGCMs. This enables rapid simulation of the impacts of a novel emissions scenario in contrast to AOGCMs that not only require hours or days of simulation time, but are generally unable to calculate concentrations from emissions or calculate many downstream impacts.

Adjustable model parameters

Adjustable model parameters allow for the simulation of different climate sensitivities or ocean heat uptake rates, among other climate and carbon variables, to emulate more complex models¹¹ and run probabilistic projections. IPCC has long used MAGICC for producing probabilistic projections²¹. Recently, the IPCC Special Report on the impacts of 1.5 °C warming¹⁴ used both MAGICC and the FaIR model²² to assess the probability of emissions scenarios staying below certain temperature thresholds.

RC models lack the chaotic behaviour

RC models lack the chaotic behaviour that accompanies more complex models using nonlinear dynamical processes²³. As such, RC models lack interannual variability, making them extremely useful for investigating small perturbations of emissions, concentrations or radiative forcing whose climate impact signal would be smaller than year-to-year variability of the Earth system. The US Government used MAGICC^{24,25} to calculate future concentrations, temperatures and sea-level rise resulting from different emissions scenarios for a rulemaking regarding vehicle efficiency²⁶; the emissions reductions from the rule were on the order of half a GtCO₂ per year, which would be difficult to resolve with a typical AOGCM.

These characteristics enable

These characteristics enable RC models to serve many uses: analysing climate impacts on multi-century timescales²⁷; investigating remaining carbon budget estimates²⁸; providing emissions and concentration inputs into CMIP models²⁹; exploring key facets of the AOGCMs they emulate, such as determining the factors driving variability on multiple timescales³⁰; and, when coupled with historical observations over the past century^{31,32}, producing estimates of transient and equilibrium climate sensitivity²⁶.

Coupled with IAMs

Coupled with IAMs, RC models enable the calculation of cost-effective policies for meeting given concentration or temperature targets^{33,34}; or in cases where IAMs include damage estimates, policies that have the highest net present value^{35,36}. One key application of IAMs is the estimation of the marginal value of emitting an additional ton of carbon. NAS recommended improvements for the development of new social cost of

CO₂ estimates³. The recommendations included an analysis of the climate components of the three IAMs that are most widely used in these estimates and found them lacking. A qualitative evaluation² of 10 RC models of the climate system based on the criteria from the NAS assessment³ concluded that three of those models were the best fit to these criteria: MAGICC, FaIR and Hector.

Table 1 |

Properties of climate computational models

Complexity	High complexity → reduced complexity			
	AOGCMs/ESMs	EMICs	RC Models	
Model type				
Example models properties	See CMIP	MIT IGSM, UVic, Bern3D-LPJ, CLIMBER, LOVECLIM, GENIE, MESMO	MAGICC, Hector, GREB	<i>FaIR, OSCAR, BernSCM, WASP, PAGE, FUND, DICE, ACC2</i>
Processor time needed to simulate a single year	Thousands of hours	Tens of minutes	Seconds or less	Near-instant
Sensitivity to initial conditions	Yes	Yes	No	No
Adjustable climate sensitivity	No	Generally	Yes	Yes
Complex, nonlinear behaviour	Yes	Yes	In some cases	Limited
Earth system subcomponents (for example, ocean acidification, sea-level rise)	ESMs but not AOGCMs	Generally	Several	Possible

Models with open-source code are italicized. Some models (for example, ACC2, UVic, MIT IGSM and others) are not italicized but may have code available on request. IAMs contain economic components in addition to climate components and are bolded. Categorizations in this table are generally qualitative as assessed by the authors; some models within a category may not match all the generalizations for that category.

Table 2 |

Sample applications and relevant characteristics of RC models

User/application		Emblematic characteristic
Users	Government	Open source and transparent
	Academics	Scientific accuracy
	Public	Ease of use
Nongovernmental organizations/industry groups		Clear licensing
Applications	Climate damages	Earth system components
	Uncertainty analysis	Well-calibrated input parameters
	Aerosol impacts	Land/ocean and hemispheric differentiation
	Multi-century simulations	Multiple ocean layers
	Non-Representative Concentration Pathway scenario analysis	Ability to emulate general circulation models

While any given user or application will benefit from a model that excels at a combination of characteristics, we show a single, emblematic characteristic for each example.