Simplifying the world of simple climate models

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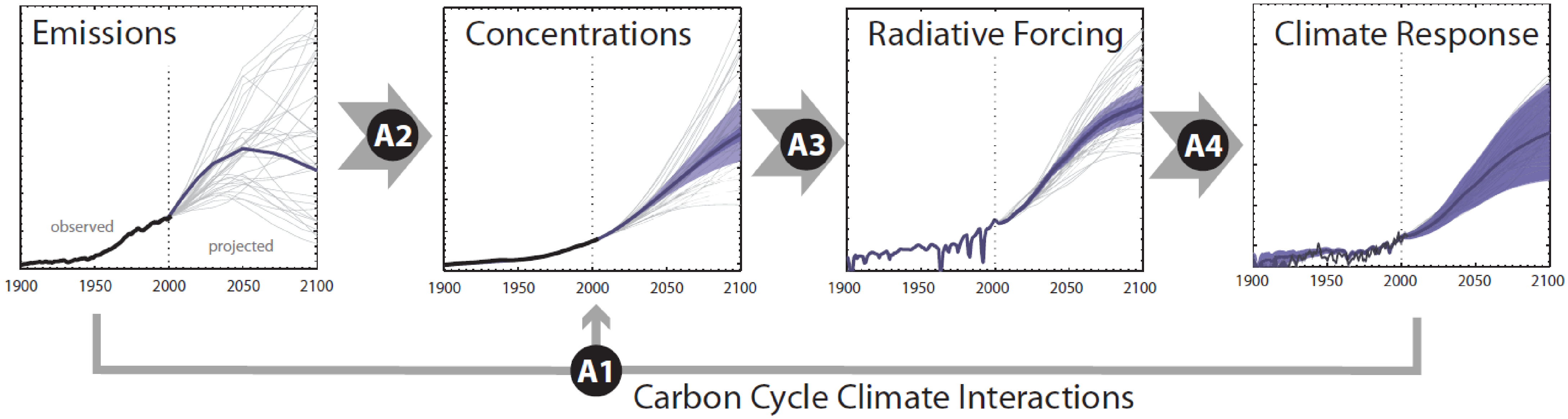
The climate community uses computational models to project climate change, but no single model is suited for every situation.

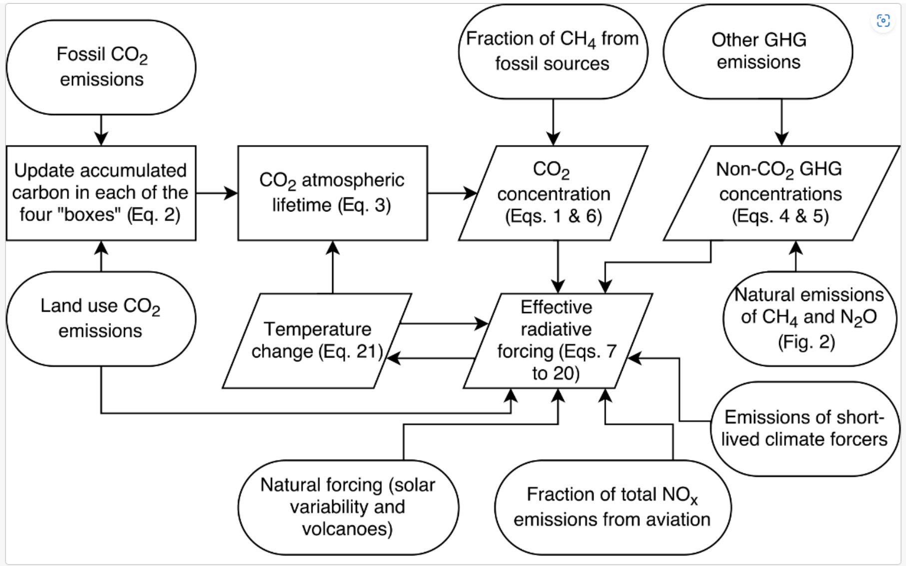
- While ESMs are integral to our current understanding of how the climate system responds to GHG and aerosol emissions and provide the most comprehensive projections of what a future world might look like, they are so computationally expensive that only a limited set of experiments are able to be run.
- This constraint on the quantity of experiments necessitates the use of simpler models to provide probabilistic assessments and explore additional experiments and scenarios.
- Simple climate models (SCMs, reduced complexity or climate emulators), range from idealized, function-based models that only project global mean temperatures to process-driven models that project multiple variables with regional resolution.
- These models are typically designed to emulate the responses of the more complex models.

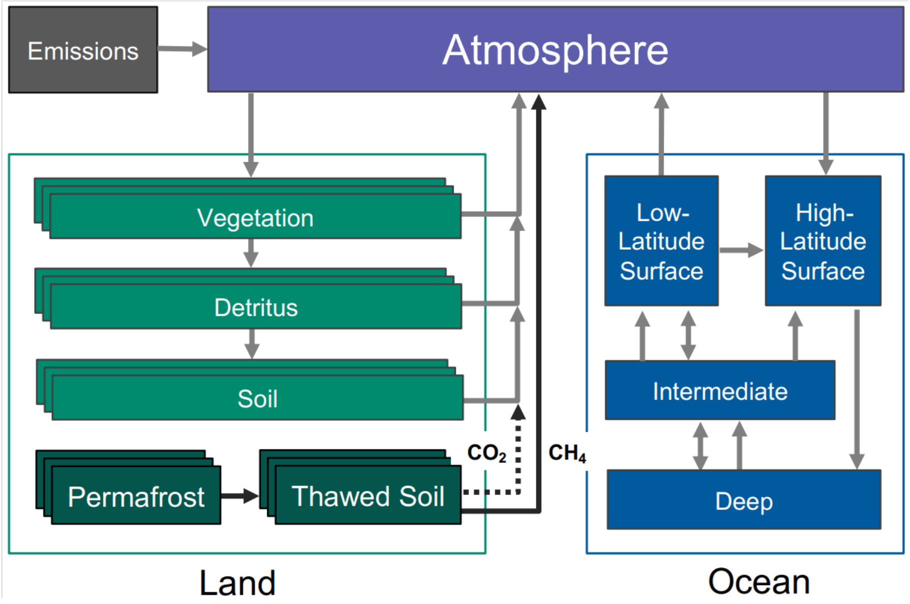
From emissions to temperature change

Global emissions – concentrations – radiative forcing – climate response



Meinshausen et al., 2011





Generalized overview of simple climate models (SCMs)

- SCMs tend to be globally averaged (or cover large regions) and parameterize many processes, resulting in many fewer output variables.
- FaIR, Hector, MAGICC, + many others (Nicholls et al., 2020 - GMD)
- Main Inputs:
  - Anthropogenic Emissions: CO_2, CH_4, N_2O, BC, OC, SO_2, 20+ halocarbons
  - Natural Emissions: CO_2, CH_4, volcanic, etc.
- Main Outputs: Atmospheric concentrations, global radiative forcing, global mean temperature, ocean heat flux

Smith et al., 2018 – GMD; Woodard et al., 2021 – GMD

Advantages of SCMs

Three technical characteristics of SCMs make them preferable to complex models for certain applications:

(1) computational efficiency,

(2) adjustable model parameters and

(3) lack of chaotic behavior.

However, SCMs lack significant spatial and temporal resolution, variability, as well as detailed earth system processes.

Table 1 | Properties of climate computational models

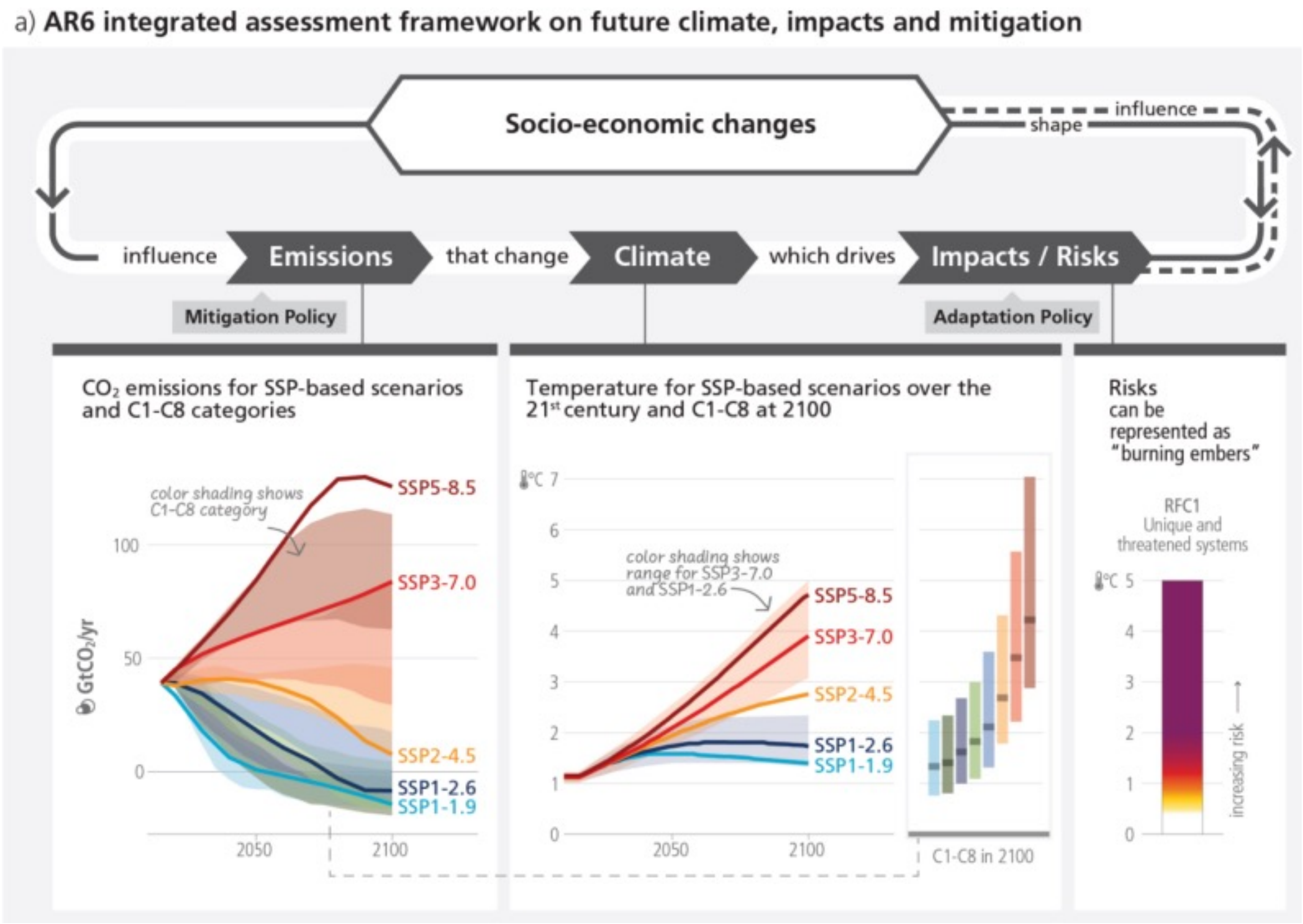
Complexity	**High complexity → reduced complexity**			
Model type	**AOGCMs/ ESMs**	**EMICs**	**RC Models**	
Example models properties	See CMIP	MIT IGSM, UVic, Bern3D-LPJ, CLIMBER, LOVECLIM, GENIE, MESMO	MAGICC, *Hector*, *GREB*	*FaIR*, *OSCAR*, *BernSCM*, *WASP*, **PAGE**, **FUND**, ***DICE***, ACC2
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.

Sarofim et al., 2021 - NCC

SCMs help integrate climate science across multiple disciplines

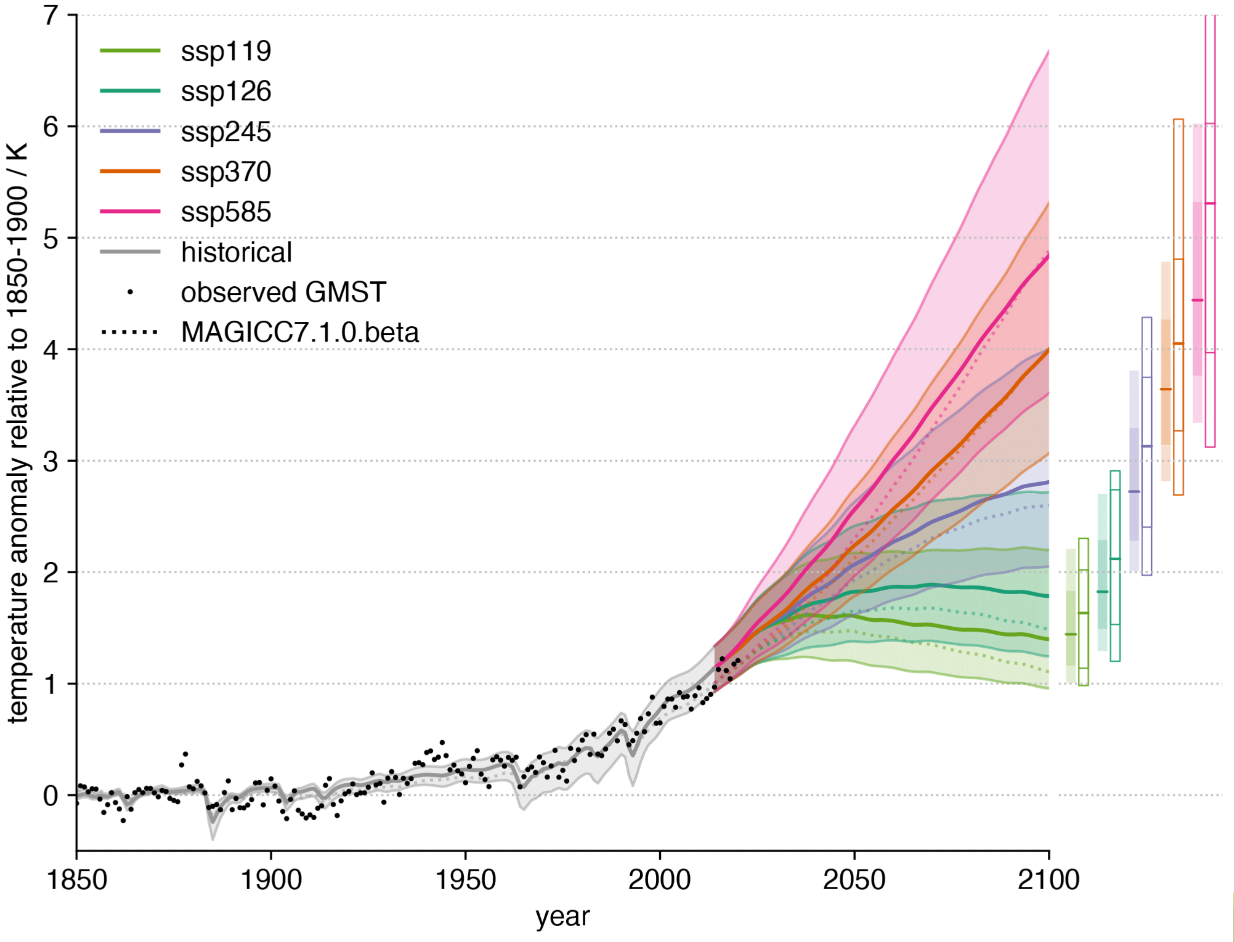
- Provide model inputs to ESMs (e.g., CO_2, CH_4, etc.)
- Evaluating the interactions between human and Earth systems (e.g., IAMs)
  - impacts
  - scenario development
- Used to evaluate
  - mitigation options
  - future probabilities
- Provide earth system inputs for decision support
- Explore fundamental science questions



AR6 Synthesis Report Cross-Section Box.2, Figure 1

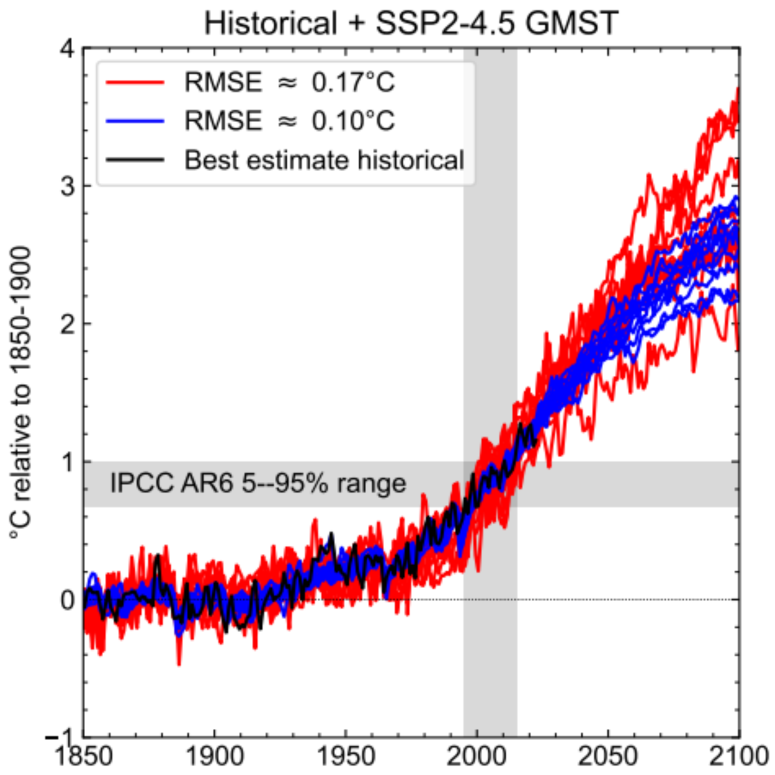
SCMs are only useful if the climate projections they provide are reliable

- It is therefore critical that emulators are calibrated to reproduce, at the very least, the time series of historical GMST to a satisfactory standard.
- The IPCC AR6 WG1 provided a rigorous calibration of four emulators against
  - historical observations of GMST
  - ocean heat content change
  - IPCC-assessed distributions of ECS, transient climate response (TCR), transient climate response to cumulative CO_2 emissions (TCRE)
  - present-day aerosol forcing
  - future projections of warming under SSP scenarios, including their uncertainties



Leach et al., 2021 - GMD

Only a small fraction of possible parameter combinations will produce historically consistent climate hindcasts.

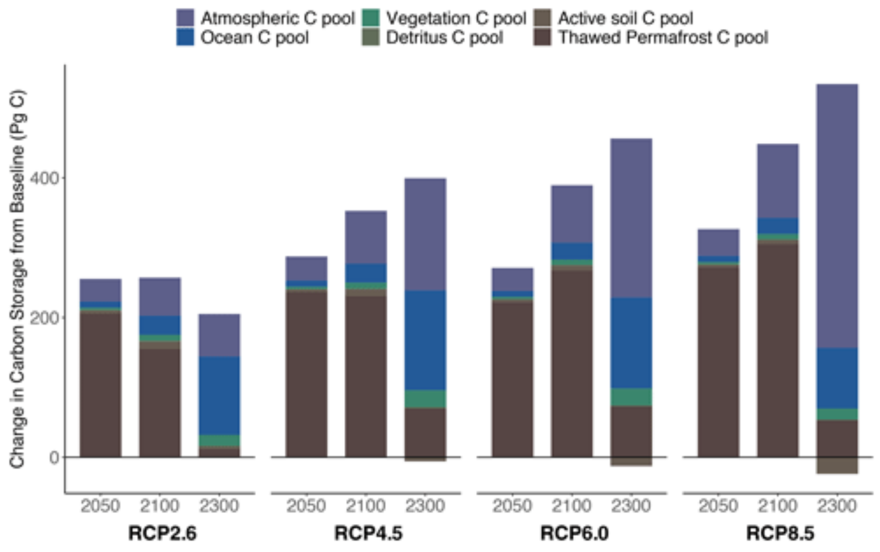


Comparison of the 10 ensemble members with the smallest RMSE error (blue) compared to the historical best estimate GMST (black) with the 10 with the largest RMSE (red) that passed this first historical constraining step

- A common way to calibrate these models:
  - Generate prior distributions of parameters based on CMIP6 ESM or IPCC assessed ranges,
  - Generate a large Monte Carlo prior ensemble of parameters
  - Produce a posterior set of parameters constrained on several observable and assessed climate metrics
  - Different calibrations can be produced for different emissions datasets or observed climate constraints, allowing version-controlled and continually updated calibrations to be produced
  - Both FaIR and Hector have user-friendly R packages to calibrate the models.

Smith et al., EGUsphere [preprint]

Some SCMs contain extra features to better capture the global climate

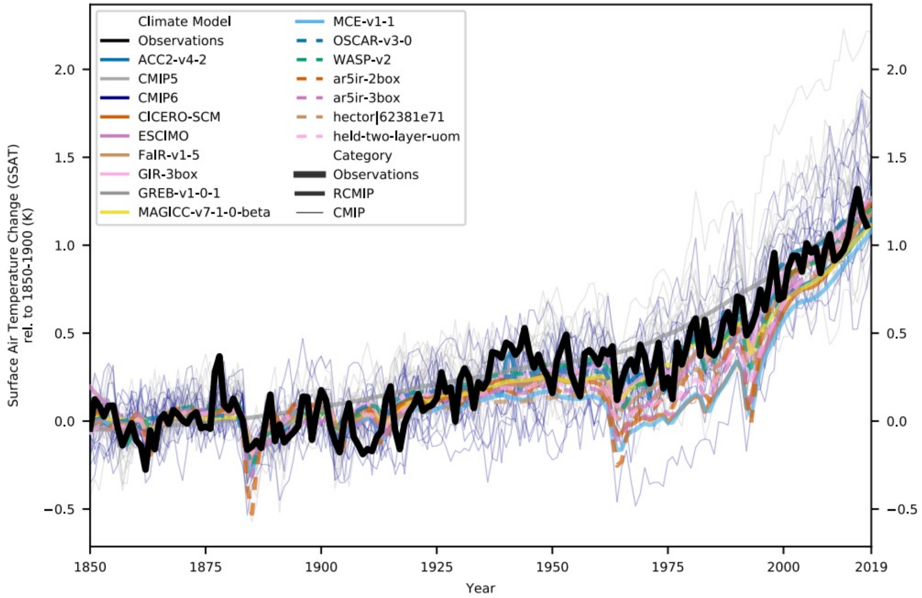


Woodard et al., 2021 - GMD

- MAGICC differentiates its forcings over land and ocean. This is particularly important for short-lived aerosol impacts (predominantly over Northern Hemisphere land masses) which differ from those of well-mixed greenhouse gases.
- Hector contains a permafrost land carbon pool that becomes available for decomposition into both CH_4 and CO_2 once thawed. The thaw rate is controlled by region-specific air temperature.
- Dynamic ocean components that model heat uptake allow for different adjustment timescales to different emissions (i.e., black carbon v CO_2)
  - Models with ocean heat content to be better coupled to sea-level rise models (i.e., BRICK)

The future of SCMs

- The National Academy of Sciences provided criteria on the use of SCM
  - consistency with scientific understanding
  - emissions pulse adjustment timescales
  - transparency and simplicity
  - incorporation of non-carbon dioxide forcings
  - ability to turn individual components on and off for testing
  - the inclusion of additional climate end points, such as sea-level rise and ocean acidification
  - the capacity to perform uncertainty propagation
- The growing use of SCMs will benefit from a structured and independent assessment like RCMIP, identify which models are superior for specific purposes.
  - 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.
- Additional features: such as whether the code is open source, if user guides exist, simplicity of the model structure, user-friendliness or computational platform requirements



Nicholls et al., 2020 - GMD