Do simplified climate models have any useful skill?

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Numerical models are important research tools in climate dynamics because they permit the quantitative testing of hypotheses regarding mechanisms of climate change. The importance of the deep ocean circulation for climate variability and rapid climate change was recognized some 40 years ago by Henry Stommel (Stommel, 1961), because dynamical ocean components need to be included in climate models. This requirement posed a serious challenge to the modellers, because now adjustment processes associated with the deep ocean needed to be included in these models. Simulation times thus increased from a few decades to centuries and millennia. More importantly, it introduced significantly more degrees of freedom into these models with unexpected consequences such as climate drift, multiple equilibria and many others.

There are several ways to take this challenge. First, the early development has focused on coarse-resolution models of the coupled atmosphere-ocean system. The representation of fundamental processes was limited in these models with the consequence that unrealistic flux corrections had to be used to stabilize simulations. Although these involved local sources of heat, freshwater and momentum, many useful predictions could be made that fuelled scientific development and shaped our thinking (e.g. Manabe and Stouffer, 1988). Over the last decade, with the growing availability of computing power, the grid resolution of these models has been steadily refined, and the parameterisations of important processes have been improved: flux corrections are no longer necessary in current coupled models (IPCC, 2001). One might therefore be tempted to conclude that the days of coarse-resolution models are over. This would be premature, however. Both paleoclimate research and the study of natural climate variability and climate sensitivity still depend heavily on climate models of comparatively low resolution. If used judiciously, they continue to contribute significantly to the scientific progress.

A second possibility is the development of simplified models. Usually, such models are derived from the full set of equations by suitable averaging processes. Energy balance models of the atmosphere (Sellers, 1969), the radiative convective models (Manabe and Wetherald, 1967), the Lorenz model (Lorenz, 1963), and the Stommel box model for the thermohaline circulation (Stommel, 1961) are extreme examples of such rigorous averaging. In spite of their limitations, it should be recognized that these models represented key steps towards an understanding of the Earth system and have been very useful in elucidating some fundamental concepts such as climate sensitivity, near-constancy of relative humidity in a warming world, multiple equilibria of fluid flow regimes, and principles of predictability in the climate system. Both the Lorenz and the Stommel models are important examples of how extremely simplified models can change completely our view of the climate system. The skill of these types of models does not lie with their ability to make specific climate predictions, but with the potential to demonstrate fundamental dynamical concepts which subsequently must be tested with more complex models. Furthermore, these models permit exploration of parameter space in a systematic way. In essence, such models only make sense within a *hierarchy* of models, with which a thorough investigation of processes is possible. Table 1 (page 8) shows such a hierarchy of models ordered according to the number of simulated dimensions in ocean and atmosphere, respectively.

The third possibility is to accept certain compromises regarding the model complexity. This is illustrated by models that populate the centre of this model hierarchy (grey shading in Table 1). These models of reduced complexity involve more processes and dimensions than the simplified models mentioned above, but they are still orders of magnitude simpler than general circulation models. Due to their low computational burden, these models have become increasingly popular in the last few years. This is manifested by special sessions at conferences, the proposal of intercomparison projects, and ongoing activities in many institutes worldwide. These "coupled models of intermediate complexity" (Stocker et al., 1992b), now referred to as *Earth System Models of Intermediate Complexity* (EMICs) (Claussen et al., 2002), are convenient research tools especially for paleoclimatic modelling and ensemble simulations of future climate change. It must be emphasized, however, that such simplicity is equally tempting and treacherous. Application of these models and interpretation of the results requires experience and caution because of the many implicit limitations in terms of their dynamics.

More than in comprehensive models, simplified models must use parameterisations with tunable parameters. Such tuning is dangerous and conclusions must be independent of small changes to such parameters. The real goal for these models is not only to reproduce certain observations or paleoclimatic records as perfectly as possible, but to make *testable predictions* about the dynamical behaviour of the climate system, e.g., the response of the southern hemisphere to a reduction of the Atlantic thermohaline circulation, (Stocker et al., 1992a). In addition, these models are very useful to construct ensemble simulations. With such ensembles, uncertainty in climate change projections can be quantified in an objective way (Knutti et al., 2002).

Table 1: Climate model hierarchy. This is only a "projection", since complexity in components such as the cryosphere, land surface and the biogeochemical cycles is not displayed here. Coupled models of reduced complexity (Earth System Models of Intermediate Complexity, EMICs) are shaded in grey. Specific examples of models with their names of reduced complexity are given in bold italics.

Dimension	**Ocean**			
	0	**1**	**2**	**3**
Atmosphere 0	global EBM *Saltzman Models* pulse response models	global mixing models geochemical box models advection-diffusion models, ***HILDA***	thermohaline models (lat/z): wind-driven circulation models (lat/long) deep ocean models (lat/long)	OGCM
Atmosphere 1	EBM (lat) radiative-convective models (z)	–	ocean (lat/z) + EBM (lat) ***BERN2.5D***	–
Atmosphere 2	EBM (lat/long)	statistical dynamical atmosphere + diffusive ocean, ***MIT 2D***	ocean (lat/z) + statistical dynamical atmosphere (lat/long), ***CLIMBER2*** ocean (lat/z) + stat. dyn. atm. (lat/z), ***MOBIDIC***	OCGM + EBM (lat/long) ***UVIC*** OCGM + QG atm. ***ECBILT***
Atmosphere 3	AGCM + SST	ACGM + mixed layer	ACGM + slab ocean	**A/OGCM**

A fourth approach, which complements the model hierarchy, is to build substitute models. More complex models are represented by either linearizing them by so-called *pulse-response models*, or by constructing substitutes based on sophisticated approximation methods. A recent promising avenue is to employ *neural networks* and train these networks with results from climate models (Knutti et al., 2003). For example, the neural network representation of the BERN2.5D model is several orders of magnitude more efficient than the original model, once training of the neural network is completed (Fig. 1). This opens unexplored possibilities with such climate model substitutes. In the future, climate models not only need to provide reliable projections of climate change, but they are also expected to yield quantitative estimates of uncertainties. Ways how to calculate such uncertainties, and how to constrain them with available observations have been demonstrated in the framework of reduced complexity models. Rather than giving final predictions, these simplified models thus exhibit their skill by serving the community to explore new methodologies at comparatively low cost. The lessons learned can then be applied to comprehensive, state-of-the-art climate models.

Simplified models also give access to long time scales extending over many 10,000s of years. To investigate climate changes on these time scales, large ice sheets must be included in such models. Efficient models of intermediate complexity have filled this gap which is currently inaccessible for comprehensive models, and have provided insight into the possible ocean-ice sheet feedbacks involved in abrupt climate change (Calov et al., 2002; Schmittner et al., 2002).

The limited degrees of freedom in simplified models is responsible for the fact that they often underestimate natural variability. This may lead to a general bias towards deterministic interpretations in explaining mechanisms of climate change. Some recent studies with reduced complexity models including both atmospheric and oceanic variability suggest that natural variability could have played an important role in, e.g., the occurrence and duration of abrupt climate events (Renssen et al., 2001; Goosse et al., 2002).

Reduced complexity models have also become increasingly important as "integrators" in climate research (Alverson et al., 2003). Records of past climate changes obtained from different paleoclimatic archives and different geographic locations are often difficult to synthesize. But simplified coupled physical-biogeochemical climate models can provide crucial help in integrating diverse pieces of information which otherwise could not be interpreted. This is particularly evident in cases where information about biogeochemical cycles needs to be

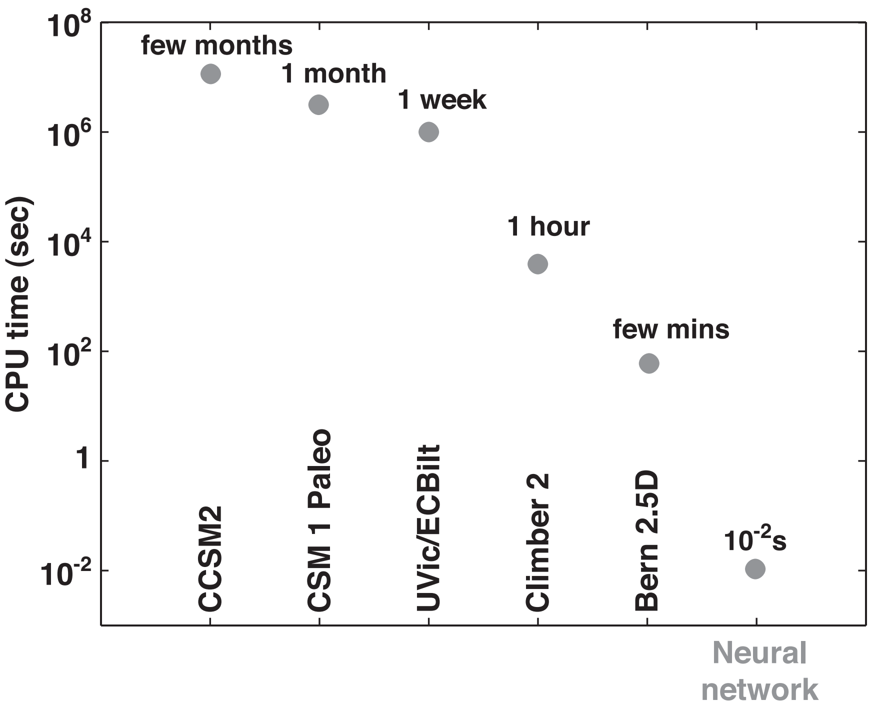

Fig. 1: Comparison of very approximate estimates of CPU requirements of a typical global warming simulation of 250 years for a hierarchy of climate models. (Knutti et al., *2003).*

combined with dynamical aspects of climate change. Whereas until recently, the geochemical community routinely relied on box models, simplified dynamical models have now matured to the stage where they can be used to investigate problems related to physical-biogeochemical interactions in the climate system. For example, the potential and limitation of new paleoceanographic tracers has been assessed by such models (Marchal et al., 2000). The inclusion of simplified formulations of the terrestrial vegetation cover permits the investigation of new feedback mechanisms in the climate system that might be crucially important to understand past and future climate change (Brovkin et al., 1999; Claussen et al., 1999).

Before wide-ranging conclusions are drawn based on simplified models, however, it is important that consistency with dynamically more complete models be checked. One recent example concerns the role of the high latitude oceans in determining changes in the atmospheric CO_2 concentration. A thorough comparison of the effects in the carbon cycle model hierarchy ranging from box models to comprehensive OGCMs revealed that the simplified representation of mixing in the high latitudes employed by box models resulted in an overestimation of the link between meridional overturning in the Atlantic and atmospheric CO_2 concentration (Archer et al., 2003). Two-dimensional models of intermediate complexity, on the other hand, showed a behaviour that was consistent with that of the comprehensive OGCMs. This demonstrated that for this particular application, the reduced complexity models already contained sufficient detail to provide a consistent answer. It is obvious that such agreement cannot be taken as a general license, but that consistency with more comprehensive models and/or observations must be checked, where possible, for each application.

The increasing importance of climate models that occupy the intermediate realm of the model hierarchy has also been highlighted by the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2001) which contained a subsection on this type of models and presented results from long-term simulations on the evolution of sea level rise, carbon uptake and other slowly adjusting quantities in the climate system. While the standard IPCC scenario calculations have traditionally been performed with box models, models of intermediate complexity are now ready to be used for extensive calculations necessary for upcoming assessment and technical reports under the auspices of IPCC.

Apart from paleoclimate modelling, where models of reduced complexity have already been applied successfully to study processes on long timescales of thousands to millions of years, efficient climate models could probably be used more extensively in the field of Integrated Assessment (Nordhaus, 2001). Contributing to assessment efforts such as IPCC, economic models and climate models are often used separately and sequentially by first developing a scenario of the future (in terms of population, economy, energy demands, etc.), calculating climate change for a given fixed scenario, and finally estimating impacts, costs or benefits in a third step. However, interactions between political decisions and climate change could become important in the future in defining and modifying a scenario. This would impact mitigation strategies and optimization of emissions paths for future development at minimal damage or energy cost. Such efficient coupled climate-economy models could contribute to close the gap between scientists, politicians and economists. This would represent a quantum leap in designing new strategies for coping with future climate change.

While simplified models occupy an important place in climate dynamics, their developers and users bear a special responsibility. It is only through extensive parameter exploration and ensemble simulations that these models provide added value in climate studies. If used judiciously, they serve as "hypothesis generators" and actually represent useful precursors to subsequent targeted simulations with more complete climate models.

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