# The utility of Earth system Models of Intermediate Complexity (EMICs)

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Intermediate-complexity models are models which describe the dynamics of the atmosphere and/or ocean in less detail than conventional General Circulation Models (GCMs). At the same time, they go beyond the approach taken by atmospheric Energy Balance Models (EBMs) or ocean box models by using sophisticated parameterizations of the unresolved flow or by explicitly resolving the equations of geophysical fluid dynamics albeit at coarse spatial resolution. Being computationally fast, intermediate-complexity models have the capability to treat slow climate variations. Hence, they often include components of the climate system that are associated with long-term feedbacks like ice sheets, vegetation and biogeochemical cycles. Here again they differ from conventional GCM-type models that feature only atmosphere and ocean/sea-ice components. Many different approaches exist in building such a reduced model, resulting in a 'spectrum of Earth system Models of Intermediate Complexity closing the gap between EBMs and GCMs'. © 2010 John Wiley & Sons, Ltd. *WIREs Clim Change* 2010 1 243–252

The present paper discusses different types of intermediate-complexity models and the phenomena for which they are most suitable, comparing their utility to General Circulation Model (GCM)-type models. Earth system Models of Intermediate Complexity (EMICs) have been widely applied over the last decade in research which often would not have been feasible with GCMs, such as large-ensemble scenario simulations of potential future climate change and the study of climate variations ranging from rapid events to glacial cycles and Milankovitch timescales. This has yielded substantial knowledge and a range of hypotheses on the working of the climate system.

Many approaches exist to modeling the climate system. These range from conceptual models, like atmospheric energy balance models (EBMs) and ocean box models, to complex GCMs of the atmosphere and/or ocean. The first type of models are based on *a priori* concepts of the functioning of (specific aspects of) the climate system. They are designed to be computationally efficient. In many cases they may be expressed in the form of simple dynamical systems,[1] the steady state of which may be computed analytically. GCMs, on the other hand, only became feasible because the birth of high-speed computers in the 1960s. As computing power has grown exponentially over the last decades, GCMs could become increasingly more complex.

## CONCEPTUAL VERSUS COMPLEX MODELS

EBMs[2,3] solve the radiative heat balance of the atmosphere in terms of the surface air temperature. In their simplest zero-dimensional form they describe the global heat budget. They also exist in one-dimensional (latitudes) or two-dimensional form (latitudes and longitudes), generally with diffusive horizontal heat transport. EBMs have been widely applied, e.g., to the study of glacial cycles, bistability associated with the ice-cap albedo feedback and future climate change, see the review paper by North et al.[4] The oceanic counterparts of EBMs are so-called box models, where the boxes represent reservoirs with different temperature and salinity. This type of model was developed to study the density-driven circulation

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between reservoirs, an analog for the large-scale ocean circulation, which was found to exhibit two stable regimes of flow.[5] Many extensions of these basic concepts have been proposed, including coupled EBM-Stommel models.[6] Even though they are simple, conceptual models may have quite complex behavior.

GCMs solve the fundamental equations of motion, together with those for the evolution of temperature and moisture (atmosphere) or temperature and salinity (ocean). They also contain parameterizations of processes that occur on small spatial scales which cannot be explicitly resolved, like cloud formation, the turbulent exchange of heat, moisture, and momentum at the air–sea and air–land interfaces, deep convection in the ocean, etc. These parameterizations (i.e., descriptions in terms of the resolved variables) are generally based on observational or high-resolution numerical process studies. GCMs generally need some 'tuning' to reproduce observations. This is done by adjusting parameters in the dynamical equations or in the parameterizations in such a manner that observational structures appear, as faithfully as possible, like the mid-latitudes storm track or the ocean thermohaline circulation. Modern computer power allows high spatial resolution for the resolved scales and sophisticated parameterizations of small-scale processes. The climate simulated by GCMs has thus become increasingly more realistic.[7]

The gap between conceptual models on the one hand and GCMs on the other hand has steadily widened over time, as GCMs became increasingly more complex and thus more difficult to understand. This has called for an intermediate class of models that combine a conceptual approach with complexity.[8,9] They incorporate more phenomenological assumptions than a GCM, like zonal averages, the observed vertical structure of the atmosphere or the shape of its large-scale circulation cells. They are less transparent than purely conceptual models and they are more likely to produce information that cannot be foreseen from their basic assumptions and that could possibly be in conflict with observations. There is a practical side too. State-of-the-art GCMs are made typically at national facilities by 'an army of foot soldiers' to do the modeling work, with the aim to run a few experiments (e.g., a 100-year forecast) once on the largest computer available. This type of model development is often not feasible for a small research institute or university department that may have access to less computer power. At the same time there are limits set by computer resources to the use of state-of-the-art GCMs as research tools to systematically explore a scientific question. Therefore, both scientific and practical reasons led to the invention of intermediate-complexity models that can be developed by relatively small teams and can be run for long time scales or many times, while being more realistic than conceptual models.

Climate research has evolved over the last decade toward an integrated approach that considers more components of the Earth system than just the atmosphere and ocean, like the biosphere, land ice, biogeochemical cycles, and atmospheric chemistry. Intermediate-complexity models are eminently suitable to explore interactions between the various components. These two lines of development have resulted in earth system models of intermediate complexity (Ref 10). EMICs are denoted as *intermediate-complexity* models, because they describe the climate system in less spatial and temporal detail than GCMs and they include processes in a more parameterized form. They are simple enough to allow for long-term or large-ensemble simulations. In contrast to conceptual models, the number of degrees of freedom of EMICs exceeds the number of adjustable parameters by several orders of magnitude.[10] EMICs are useful tools to tackle the wide range of processes which are effective in changing the climate over a range of timescales. Their continued development is often driven by research questions that emerge from the study of climate variations in the past as well as possible future climate change.

## THE SPECTRUM OF EMICS

EMICs come in many different varieties. Here we distinguish two principal aspects: the level of complexity of the atmosphere and ocean modules and the (number of) other components of the Earth system that are included. These two aspects are discussed in the following subsections. An overview of EMICs is given by Claussen et al.[10] There is an EMICs network, which maintains a website where an updated overview can be downloaded, see under Further Reading at the end of this paper. This Table of EMICs contains detailed technical descriptions, an extensive list of references and contacts for each model.

### Intermediate-Complexity Atmosphere–Ocean (AO) Models

An important impetus to develop fast atmospheric models was the study of climate variations on Milankovitch timescales and glacial-interglacial cycles. For this purpose EBMs were extended to two dimensions, taking the land–sea distribution and seasonal cycle into account.[11] A more advanced approach was taken by Gallée et al.,[8] who developed a zonally averaged quasi-geostrophic (QG) atmospheric model. Such a model resolves meridional transports and is thus suitable for coupling to an ice-sheet model. Both models were used to study the atmospheric response over several hundreds of thousands of years, the step forward taken by Gallée et al.[12] being the inclusion of a dynamical ice-sheet model (cf. next section)

A second application of fast atmospheric models was the study of the large-scale ocean circulation and its role in the climate system. Here one needs simple atmospheric models to provide heat and freshwater boundary conditions that reflect the main atmospheric feedbacks on variations in the ocean circulation. Therefore, EBMs were extended to also describe the atmospheric moisture budget.[9] Generally moisture transport is parameterized in EBMs in a similar way as the heat transport, namely, by diffusion. It is not necessary to compute the time-dependent behavior of the atmosphere for this application, because the atmosphere adjusts on a short timescale to the ocean and focus is on the long-term variations in the ocean. Boundary conditions, which can be derived from the equilibrium heat and moisture budgets, can also represent the atmospheric feedbacks.[13,14] Some versions of moist EBMs include advection by climatological (prescribed) winds,[15] thus improving the description of zonal transports by continental or marine air masses and meridional moisture transport in the tropics where the transport is counter gradient. Alternatively, wind stress and moisture transport are diagnosed from temperature gradients.[16]

Statistical dynamical (SD) models of the atmosphere explicitly solve the fundamental equations of motion for part of the flow, while containing sophisticated parameterizations of the unresolved flow and associated transports.[17,18] In general, they simulate more spatial detail than EBMs. They also contain some representation of synoptic variability and the tropical circulation cells, without having to prescribe these from climatology. On the next level of complexity, there are three-dimensional atmospheric models based on the QG approximation or the full primitive equations (PE). Examples are the QG atmospheric model ECBilt,[19] which contains a parameterization of the unresolved ageostrophic flow, and the PE models Portable University Model of the Atmosphere (PUMA)[20] and SPEEDY.[21] The PE models could very well be described as a simplified coarse-resolution AGCM. They are included in the discussion here, because they differ from GCMs in that they contain a parameterization package that is specifically designed and tuned for their coarse spatial resolution.

On the ocean side, there is less variety. Some atmospheric modules are coupled to mixed-layer oceans, representing a heat reservoir without dynamics. Ocean circulation models are either zonally averaged over separate basins[22] or three dimensional. The former represent the meridional flow, with a parameterization of the zonal pressure gradients that drive the flow. The wind-driven circulation is obviously neglected in this approach. Three-dimensional models are mostly PE, but simplified systems based on geostrophy have also been developed.[23] Sea-ice modules within the ocean component are thermodynamic models in their simplest form, but can be more advanced including sea-ice dynamics and/or advection.

Different modeling groups have taken different views on how to design a coupled AO model of intermediate complexity. This has resulted in a diverse spectrum of models, with either the atmosphere or the ocean in a reduced form and the other component modeled in a more comprehensive manner, or both components reduced. There also exist intermediate-complexity models which have both components at a level of complexity that is close to GCMs. The most widely applied EMICs range from a sophisticated OCGM coupled to an EBM atmosphere (UVic 24) or a QG atmosphere (ECBilt-CLIO; 25), to a zonally averaged ocean coupled to a zonally averaged QG atmosphere (MoBiDic; 26), a SD atmosphere (CLIMBER; 18) or an EBM (Bern2.5D; 9) and finally a mixed-layer ocean coupled to a PE atmosphere (PUMA; 20). One model (GENIE; 27) is specifically set-up in such a way that different components of varying complexity can be combined, depending on the research question.

## Other Components of the Earth System

Many EMICs include other components beside the atmosphere and ocean, although this is not true for all EMICs and most allow configurations that are AO only. The two most important additional components are the biosphere and land ice, while first steps are being taken to include atmospheric chemistry.

Biosphere models of varying complexity have been used. They simulate the terrestrial carbon pool[28] or the distribution of vegetation and the associated carbon and water budgets.[29,30] Some EMICs include the ocean carbon cycle and possibly the dynamics of other biogeochemical tracers.[31–33] Biosphere models generally have the same spatial resolution as the atmosphere or ocean component to which they are coupled.

Ice-sheet models are based on ice-mass conservation, with simple relations for ice flow, lateral discharge or calving.[12,34] Ice-sheet models were first coupled to the fastest type of atmospheric models (EBMs, SD, or zonally averaged QG models), which are most suited to simulate the long timescales of glacial-interglacial cycles. The most challenging aspect is to model the detailed geometry of ice sheets. In order to do this, the climate forcing has to be downscaled from the coarse resolution of the atmospheric component to the necessary small spatial scales.[35]

Atmospheric chemistry models[36] predict the concentration of reactive gases in the atmospheric, such as methane, ozone, and tens of other species. Some of these are radiatively important and thus feedback on climate, while climate influences chemical reactions through transport by winds, ambient temperatures, solar radiation etc.

A detailed overview of the components that are included in different EMICs can be found in the references given above for the individual models, the review paper by Claussen et al.,[10] the Table of EMICs or the various EMIC Intercomparison studies.[37–40] EMICs are denoted as intermediate-complexity models, primarily because of the reduced form of their AO components. Many EMICs contain ocean chemistry, vegetation, and land-ice components that are similar in complexity to those coupled to GCMs.[24]

## RESEARCH QUESTIONS

The simplifications implemented in EMICS are such that a given simulation may be performed using one to several order of magnitudes less computational steps than with a GCM. EMICs are thus computationally fast by design. However, simplifications are often made with the aim to address specific research questions. For this reason, the spectrum of climate models is not continuous. There are gaps and irregularities, implying that there is no guarantee that results obtained with one type of model can be reproduced with another, possibly more complex model. Keeping this caveat in mind, EMICs are eminently suitable for hypothesis testing (what-if questions). This type of research sets the scene for the analysis of observations, model-intercomparison studies and the design of GCM experiments. Here we will discuss a number of examples, which have been chosen specifically to illustrate the strengths and weaknesses of EMICs. There is no intention to give a comprehensive overview of research on specific topics or even of research done with EMICs. Wherever possible results obtained with EMICs will be compared with GCM-based studies that were performed at a later stage, when increased computer power allowed such experiments.

### The Transient Evolution of Climate

Many forcings of the climate system vary over time, such as orbital, solar and volcanic forcing, land use changes, or increasing greenhouse gas concentrations. GCM experiments have often considered the climatic response to these forcings in time-slices or snapshots,[41] that is, assuming equilibrium between forcing and response. This is often a useful approach. However, in many cases transient experiments can add important information and in some cases, like the deglaciation, they are essential to understand the intrinsic non-equilibrated behavior of the climate system. The length of such transient experiments ranges from a few hundred to hundreds of thousands of years, depending on the forcing and the response timescale of the system under consideration.

As noted above, an important early application of intermediate-complexity models was the study of orbital cycles in the climate system. Many paleodata reflect monsoon-driven variations, as monsoons affect climate over a large area. Because EBMs can only address the temperature evolution, more complex models were necessary to study monsoons. Phase lags in the monsoon response to orbital forcing were first studied with an intermediate-complexity model.[42] A transient OA-GCM experiment with accelerated forcing (by a factor of 100), which was conducted later by Kutzbach et al.,[43] resulted in very similar phase lags for the large-scale temperature and monsoon response as obtained earlier with reduced models.[11,42] Obviously, the GCM experiment described the evolutionary response in much more spatial detail allowing a more extensive comparison with paleodata.

Climate evolution during the last 10,000 years, the Holocene, was also first studied with EMICs. This revealed an abrupt change in Saharan vegetation[44] and gradual shifts in boreal forests[26] as the climate became drier and cooler in response to orbital and greenhouse gas forcing. The shift in boreal forests has been identified in a range of model experiments including time-slice sensitivity tests with an AGCM,[45] but its timing could only be established by a transient EMIC experiment and was found to be in reasonable agreement with paleodata.[26] A possible abrupt shift in Saharan vegetation is still under debate. Transient simulations for the Holocene were also done with other forcing factors taken into account, showing the importance of solar forcing for centennial variations at large spatial scales[46] and of remnant ice sheets for the early Holocene climate.[47] The Holocene increase in $CO_2$ concentration is not prescribed, but interactively modeled by Brovkin et al.[48] They find that this increase in $CO_2$ is driven by a decrease in terrestrial carbon storage, which was confirmed by a later GCM study.[49]

Future climate change because of increasing greenhouse gas concentrations is intensively studied nowadays. Long-term projections by EMICs, which include carbon cycle-climate feedbacks, are discussed in the latest IPCC Assessment Report.[40,50] These extend to 3000 AD, in contrast to GCM-based projections which extend only to 2300 AD. EMICs have also considered the long-term fate of the ice sheets[51] and the onset of the next glaciation, which may be delayed because of the warmer background climate.[52]

Finally EMICs are extremely useful tools to study abrupt changes in climate, like the glacial Dansgaard–Oeschger events or the Bølling–Allerød warming during the last deglaciation. This has shown that such rapid events in the Northern Hemisphere can be triggered by freshwater input into the Atlantic ocean, inducing a switch from one steady state to another one in the meridional overturning circulation.[53–55] Associated temperature changes over Antarctica are more gradual.[56] Such long experiments, starting from an equilibrated glacial state, are only starting to become feasible with GCMs. A first GCM simulation of the Bølling–Allerød warming showed a linear transient response of the overturning circulation,[57] rather than the abrupt shift through nonlinear bifurcation as found in EMICs. This discrepancy will be further discussed in the next subsection.

## The Atlantic Thermohaline Circulation

Since Stommel's[5] box-model experiments there has been a strong interest in the bistability of the Atlantic thermohaline circulation. Rahmstorf et al.[38] first studied the robustness of this behavior, which has been found in many studies with ocean-only models, in the framework of coupled AO models. They indeed found hysteresis in a range of EMICs in response to slowly varying freshwater forcing, with some models having their present-day state in the bistable regime and others in the monostable regime. The location of the present-day state in the hysteresis diagram was shown to be associated with the sign of a basin-scale salinity advection feedback in EMIC simulations by de Vries and Weber.[58]

Hysteresis experiments are as yet computationally too demanding for coupled AO-GCMs. However, shorter pulse experiments are feasible and these have been performed many times. An intercomparison study, including both GCMs and EMICs, showed a resumption of the thermohaline circulation after termination of the pulse for all models.[59] Although this study did not find any systematic differences between EMICs and coupled GCMs, it has been questioned whether hysteresis of the thermohaline circulation is an artefact of simplified models. Ocean model improvements, like new parameterizations and mixing schemes, do not affect the hysteresis behavior.[60] The question of whether including all possible atmospheric feedbacks makes hysteresis disappear can only be resolved by putting coupled GCMs to the test. First results indicate an absence of bistability,[57] but we note here that most existing GCMs seem to reside in the monostable regime.[61] Bistability has been found in one coupled AO-GCM,[62] implying that this question is open for further debate.

The climate system has exhibited rapid shifts during glacial periods, but not during the Holocene. It is, therefore, important to perform this type of experiments for a glacial background state. Hysteresis behavior was found to be less pronounced during glacial periods,[53,63] because of the coldness of the glacial climate which allows deep-water formation to retreat gradually southward in the northern Atlantic in response to surface freshwater input. Pulse experiments show that the glacial circulation is more easily perturbed, both in a coupled GCM[64] and EMIC,[65] because of the larger sea-ice extent which inhibits the restoring thermal feedback. Interactions between the continental ice sheets and the ocean are found to destabilize the glacial circulation even more.[66]

To obtain a glacial thermohaline circulation is a challenge in itself, because of the long response time of the deep ocean to glacial boundary conditions. A shallow overturning cell with reduced strength is indicated by paleodata for conditions of the Last Glacial Maximum (LGM; 21,000-years ago). EMIC experiments have suggested that this weakening is due to reduced net evaporation over the Atlantic basin[66] or to increased density of Antarctic bottom water as compared with North Atlantic deep water.[67] The latter mechanism has been confirmed by a GCM study, where it was due to enhanced sea-ice formation and export in the southern ocean.[68] One EMIC-based study found that the overturning response to cooling was nonlinear, with increased overturning strength for moderate cooling and weakened circulation for more intense cooling.[69] A model-intercomparison study of LGM experiments, including both GCMs and EMICs, showed varying responses in the thermohaline circulation—both in sign and amplitude.[61] Notwithstanding these varying responses, it was found that changes in the density contrast between deep-water masses of southern and northern origin was a controlling mechanism in the majority of models.

## Hindcasting, Assessing Uncertainties and Forecasting

Apart from long simulations, EMICs can equally well be applied to large ensembles. This allows to examine the impact of uncertainties in the design of experiments. Climate change signals recorded in paleo data which cannot easily be explained motivated diverse experiments applying freshwater pulses in the North Atlantic ocean. One example is the meltwater release attributable to the outburst flood of the proglacial lake Agassiz thought to have caused the 8.2 kyear cold event[70,71] and also the Meltwater pulse 1A released around 14.5 kyear BP with unknown location of release and apparently no climatic impact.[72] Another approach to generate an ensemble is to exploit uncertainties in model parameters. This was applied to estimate the magnitude of global-mean cooling during the LGM using empirical constraints on regional cooling inferred from paleodata[73] and to investigate the response and predictability of the climate to an increase in greenhouse gas concentration, constraining the system with modern instrumental data sets.[74] The probability density function (PDF) of, for example, the future rise in global-mean temperature has been estimated from ensembles generated by varying climate sensitivity and ocean heat uptake.[75,76] Different types of models and different constraints result in considerably different PDFs, especially with respect to the upper limit of expected climate change.[50]

# CONCLUSION

EMICs combine a conceptual approach with complexity in modeling the dynamics of the atmosphere and ocean, while often containing other components of the Earth system as well. Many different approaches exist to intermediate-complexity modeling, resulting in considerable heterogeneity in model structure and set-up. In general, EMICs are not suited to study small spatial scales and/or high-frequency variations in the climate system. They are designed for the larger spatial and longer temporal scales, where the precise definition of 'large' and 'long' obviously depends on the specific model.

EMICs have been applied to a wide range of research topics, including glacial cycles, the last glacial inception, the possible delay of the next glacial inception because of global warming, rapid climate change like the Dansgaard–Oeschger and Heinrich events, the Pliocene–Pleistocene transition, Milankovitch cycles, atmosphere–vegetation interactions in past and future climates, the Holocene carbon cycle, the ocean response to glacial boundary conditions, the effect of ocean circulation changes on atmospheric radiocarbon, the bistability of the ocean's thermohaline circulation, decadal-centennial variability and the role of solar and volcanic forcing, climate forecasting using ensemble simulations, simulation of Martian atmospheres, etc. A small selection was discussed here to illustrate the scope of EMICs. Many of these research topics cannot be addressed by GCMs, for the simple reason of computational limits—although this changes quickly because of fast increases in computer power. Apart from computational efficiency, EMICs also have the advantage of being more easy to analyze than GCMs because of their (partly) conceptual design.

How has scientific thinking been changed by this approach? From the present discussion we choose the following examples as being most illustrative of the power of EMICs:

1. The idea that human interference with climate could have long-term effects, even to the next glacial inception,[52] and the objective estimation of uncertainty in the shorter-term effects.[75,76]
2. The result that hysteresis in the ocean's thermohaline circulation is a robust feature of the AO system,[38] while the absence of hysteresis is proposed to be due to model bias rather than increased complexity.[58]
3. The finding that the Atlantic overturning circulation becomes weaker and shallower in a cold climate because of increased density of Antarctic bottom water.[67]
4. The insight that a gradual change in the forcing can result in an abrupt change in climate and vegetation in a marginal zone like the Sahara.[44]

It is not clear *a priori* how model results will be affected by neglecting some aspect of climate, like synoptic-scale variability in the atmosphere or the wind-driven circulation in the ocean. For this reason, it is essential to address research questions with a range of different models—as far as computer resources allow. Some of the EMIC-based studies discussed above have been repeated later with more complex models and even full GCMs. This has shown a few discrepancies and, in many cases, consistent results. Issues under debate are, for example, the modeling of vegetation[77] and feedbacks associated with the carbon cycle.[78] We note here that also GCM-based studies can be inconsistent among each other and any new, surprising and non-trivial result found with one model—simple or complex—can be difficult to reproduce with another. Discrepancies between EMICs and GCMs occur most notably in the dynamics of the ocean's thermohaline circulation, which exhibits multiple equilibria in EMICs but seems to respond linearly in the majority of GCMs. Because of the limited number of available studies, it is as yet not clear whether this discrepancy is due to the greater complexity of GCMs or to other causes like model bias.

Computer power has increased immensely over the last decades. This implies that today's GCMs may be considered as an EMIC in years to come. Current GCMs still contain approximations, although they are based on a fundamental form of the equations that govern the changes of properties of the atmosphere and ocean. Examples are the lack of stratospheric processes, the crude representation of mixing in the ocean or the hydrostatic approximation in the atmosphere which is now abandoned in the latest generation of high-resolution regional weather forecasting models. The definition of an intermediate-complexity model is thus not fixed, but may change over time. The extension of the spectrum of climate models with a range of EMICs has proven to be very useful. It has widened the horizon of research questions that can be addressed, thus paving the way and at the same challenging research with more comprehensive models.

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## FURTHER READING

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GENIE: www.genie.ac.uk
PUMA: www.mi.uni-hamburg.de/puma
Planet Simulator, EMIC containing the PUMA atmosphere: www.mi.uni-hamburg.de/plasim
UVic: wikyonos.seos.uvic.ca/model