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Earth system models of intermediate complexity: closing the gap in the spectrum of climate system models

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Abstract We propose a new perspective on the hierarchy of climate models which goes beyond the "classical" climate modeling pyramid that is restricted mainly to atmospheric processes. Most notably, we introduce a new indicator, called "integration", which characterizes the number of interacting components of the climate system being explicitly described in a model. The location of several model types, from conceptual to comprehensive, is presented in a new spectrum of climate system models. In particular, the location of the Earth system Models of Intermediate Complexity (EMICs) in this spectrum is discussed in some detail and examples are given, which indicate that there is currently a broad range of EMICs in use. In some EMICs, the number of processes and/or the detail of description is reduced for the sake of simulating the feedbacks between as many components of the climate system as feasible. Others, with a lesser degree of interaction, or "integration", are used for long-term ensemble simulations to study specific aspects of climate variability. EMICs appear to be closer to comprehensive coupled models of atmospheric and oceanic circulation (CGCMs) than to "conceptual" or "box" models. We advocate that EMICs be considered as complementary to CGCMs and conceptual models, because we believe that there is an advantage of having a spectrum of climate system models which are designed to tackle specific aspects of climate and which together provide the proper tool for climate system modeling.

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1 Introduction

Following the traditional concept of Hann (1908), climate has been considered as the sum of all meteorological phenomena which characterize the mean state of the atmosphere at any point of the Earth's surface. This classical definition has proven to be useful for climatology, the descriptive view of climate. However, for understanding climate dynamics, i.e., the processes which govern the mean state of the atmosphere, the classical definition appears to be too restrictive since the mean state of the atmosphere is affected by more than just atmospheric phenomena. In modern text books, therefore, climate is described in terms of state and ensemble statistics of the climate system (e.g., Peixoto and Oort 1992). The climate system, according to the modern concept, consists of the abiotic world, the geosphere, which is sometimes called the physical climate system, and the living world, called the biosphere. The geosphere is further subdivided into open systems, namely, the atmosphere, the hydrosphere (mainly the oceans, but also rivers), the cryosphere (inland ice, sea ice, permafrost and snow cover), the pedosphere (the soils), and the lithosphere (the Earth's crust and the more flexible upper Earth's mantle). Kraus (2000) even included human activities as part of the biosphere and, thus, the climate system. However, this very far-reaching view creates problems as human activities can hardly be described by using the thermodynamic approach. Therefore, Schellnhuber (1999) and Alcamo (1994) suggested the term Earth system to encompass the anthroposphere, i.e., human activities, and the natural Earth system, or synonymously, the ecosphere or the climate system (Claussen 2000).

The modern concept of climate is rarely reflected in discussions of climate models. For example, coupled general circulation models of the atmosphere and the ocean (CGCMs) are considered as "the most complete type of climate models currently available" (Henderson-Sellers and McGuffie 1987). Recently, Grassl (2000) stated that CGCMs will become a basis for Earth system models that describe the feedbacks of societies to climate anomaly predictions. Grassl (2000) further suggested that parametrization of vegetation and other processes and boundary conditions in CGCMs has to be improved. This view potentially underestimates the role of vegetation dynamics and biogeochemical cycles in affecting the climate system and overestimates the importance of high spatial resolution and comprehensiveness.

Here we argue that the description of the natural Earth system, or the climate system, should rely not only on CGCMs, but on a spectrum of climate system models. The proposed spectrum explicitly acknowledges the degree of "integration" (interaction) of various components of the climate system, and it leads to the concept of models of intermediate complexity.

2 Models of the natural Earth system

Marked progress has been achieved during the past decades in modeling the separate elements of the geosphere (e.g., Grassl 2000) and the biosphere (e.g., Cramer et al. 2000). This stimulated attempts to put all separate pieces together, first in the form of comprehensive coupled models of atmospheric and oceanic circulation, the CGCMs mentioned, and eventually in the form of climate system models (CSMs) which include also biological and geochemical processes (e.g., Foley et al. 1998; Cox et al. 2000). Comprehensive models of global atmospheric and oceanic circulation describe many details of the flow pattern, such as individual weather systems and regional currents in the ocean. The major limitation in the application of these models to long-term climate studies arises from their high computational cost. Even using the most powerful computers, only a very limited number of multi-decadal experiments can be performed with such models.

At the other end of the spectrum of complexity of natural Earth system models are the conceptual or tutorial models. (The term "complexity" is used here with respect to the detail of description and number of processes included explicitly, see later, but not in a mathematical sense. Also simple models can exhibit complex behavior.) These models are simple mechanistic models which are designed to demonstrate the plausibility of processes. For example, Paillard (1998) reproduced the long-term climate variations during the last one million years, i.e., the variations between rather short interglacial and longer glacials, by exploring the consequences of simple hypotheses. He assumed that long-term climate changes are triggered by summer insolation at northern high latitudes and that there are multiple states in the natural Earth system. The system was allowed to switch from one state to another if changes in insolation exceed some *ad hoc* defined thresholds.

Differentiation between conceptual and comprehensive models is certainly not new. This concept is also reflected by Saltzman's (1985, 1988) classification of inductive and quasi-deductive models. Inductive models, according to Saltzman, are formulated based on a gross understanding of the feedbacks that are likely to be involved. The system of equations, generally restricted to a very few, are designed to be capable of generating the known climatic variations, or as many lines of observational evidence as possible. The inductive approach is, to cite Saltzman (1985), "bound to be looked upon as nothing more that curve fitting, a charge that is fundamentally difficult to refute". Essentially, the predictive value of conceptual models is rather limited. Inductive models are the opposite of comprehensive, quasi-deductive models which are, with respect to their main components, derived from first principles of hydrodynamics. Quasi-deductive models include, however, many inductive components which are implicitly hidden in the parametrization of subgrid-scale processes.

The IPCC (Intergovernmental Panel on Climate Change; Technical Paper by Harvey et al., see: Houghton et al. 1997; see also Chs. 1 and 8 of the IPCC Third Assessment Report, Watson et al. 2001) followed the terminology of simple and comprehensive models. The former include box models which are tuned to mimic the sensitivity of comprehensive models. Simple models mainly serve to extend and interpolate, by physical reasoning, the results of comprehensive models to a much larger number of different scenarios associated with changes of boundary conditions.

3 EMICs and the spectrum of climate system models

To bridge the gap between conceptual, inductive, simple and comprehensive, quasi-deductive models, Earth system models of intermediate complexity (EMICs) have been proposed. EMICs are designed to describe the natural Earth system excluding the interaction of humans and nature; humans appear as some external driving force. Hence a more appropriate acronym would be NEMICs (Natural Earth system Models of Intermediate Complexity) instead of EMICs. However, the latter acronym has now been widely used.

EMICs can be characterized in the following way. EMICs include most of the processes described in comprehensive models, albeit in a more reduced, i.e., a more parametrized form. They explicitly simulate the interactions among several components of the natural Earth system, mostly including biogeochemical cycles. On the other hand, EMICs are simple enough to allow for long-term climate simulations over several thousands of years or even glacial cycles (with a period of some 100000 years, e.g., Gallée et al. 1991), although not all are used for this purpose. Similar to comprehensive models, but in contrast to conceptual models, the degrees of freedom of an EMIC exceed the number of adjustable parameters by several orders of magnitude. EMICs are mainly quasi-deductive models, rather than inductive models, although some of the components of an EMIC could belong the latter class.

Pictorially, we may define an EMIC in terms of the components of a three-dimensional vector (Claussen 2000): *integration*, i.e., the number of interacting components of the natural Earth system being explicitly described in the model (hence the term integration is used here in the sense of *integrated modeling* rather than in its original mathematical meaning), the number of *processes* explicitly simulated, and the *detail of description* (See Fig. 1).

Figure 1 provides a crude sketch of the location of the three model classes under discussion in the three-dimensional space defined already. Typically, EMICs have less detail of description than comprehensive models, but much more detail than conceptual models. EMICs include fewer processes than comprehensive models, but a higher number of interacting components and vice versa compared to conceptual models. For clarity we have overemphasized the differences between the model classes. In practice, there may be no such large gaps as suggested by the figure between conceptual models, EMICs and comprehensive models.

3.1 Spectrum versus pyramid

The proposed model spectrum depicted in Fig. 1 explicitly includes an indicator of the modeled interactions between different components of the climate system through the vertical axis. It is our view that this model spectrum offers a more satisfactorily perspective than the earlier published climate modeling pyramid of Henderson-Sellers and McGuffie (1987).

The position of a model in the climate modeling pyramid (Fig. 2) indicates the complexity with which major processes described in atmospheric models interact: The higher up the pyramid, the greater the interactions among the processes. In the second edition of their book, McGuffie and Henderson-Sellers (1997) still use the concept of the climate modeling pyramid, but they extend the pyramid to include atmospheric chemistry as a fourth vertex. Hence this pyramid reflects some aspects of *integration*, albeit only with respect to atmospheric and near-surface oceanic processes. The classical pyramid could be extended to include integration of processes within all components of the climate system. This would lead to a multi-pod pyramid. To visualize integration with climate impact, or climate assessment, McGuffie and Henderson-Sellers (1997) suggest adding a second pyramid, upside down on top of the climate modeling pyramid, producing an "hour glass". Hence, following this example, one could add a number of pyramids, describing biospheric or oceanic models, for example, with all the pyramids merging at their apices. Applying this idea to include all components of the climate system would lead to a bundle of pyramids. We therefore find the spectrum sketched in Fig. 1 more convenient.

However, it is not only the design by which the climate modeling pyramid and our spectrum differ, but also the concept. Drawing a picture of a pyramid with a particular type of models at the top could provoke some misunderstanding. For example, Shackley et al. (1998) question the apical position of CGMCs in the context of scientifically modeling with respect to policy-relevant knowledge on future climate change. They argue that the development of climate change science and global environmental policy frameworks occurs concurrently in a mutually supportive fashion, and they interpret the dominant position of CGCMs as a social construct. In their reply to Shackley et al. (1998), Henderson-Sellers and McGuffie (1999) clearly pointed out that the climate modeling pyramid is tutorial and that one should not confuse the rather simple descriptive hierarchy of models as advocacy for CGCMs being the best models. We agree with Henderson-Sellers and McGuffie (1999), and we assume that most climate modelers would agree, although some reviewers of our papers might take the

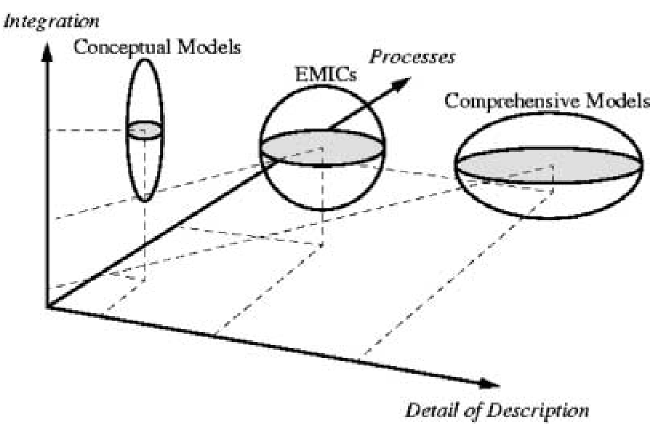

Fig. 1. Pictorial definition of EMICs. Adapted from Claussen (2000)

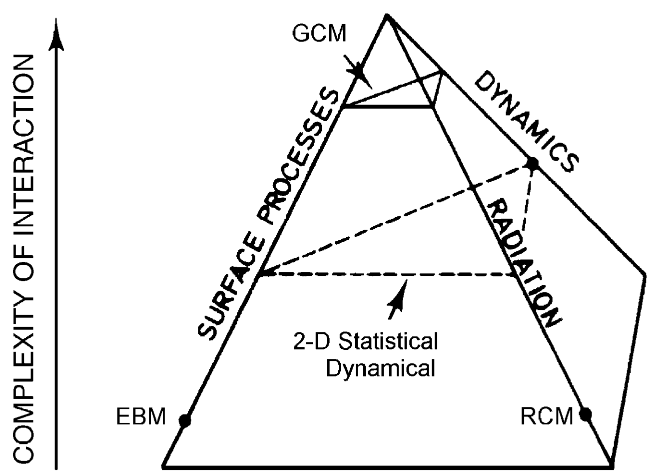

Fig. 2. The climate modeling pyramid. Adapted from Henderson-Sellers and McGuffie (1987)

opposite view. To researchers outside the climate modeling community, however, the problem is apparently not that obvious as Shackley et al. (1999) mentioned in their response to Henderson-Sellers and McGuffie (1999). Also for this reason, we prefer the phrase "spectrum of climate system models" instead of "hierarchy of climate models" or "climate modeling pyramid".

Finally, we believe that the picture of merging pyramids of various model systems through their tops, as suggested by McGuffie and Henderson-Sellers (1997) in the case of a climate modeling and a climate assessment pyramid, is not generally valid. In some cases, results of CGCMs are used for climate impact assessment. However, if climate models are to be integrated into a general assessment model, then simplified, or even strongly simplified, climate models are used (e.g., Alcamo et al. 1996; Bruckner et al. 1999; Prinn et al. 1999).

4 A survey of EMICs

The development of EMICs in various climate research centers around the world started roughly a decade ago, and today there is an active group of EMIC modelers who meet once or twice a year to exchange notes on selected results from the models and to plan intercomparison simulation experiments. This series of meetings started at the Potsdam Institute of Climate Impact Research in June 1999.

At the 25th General Assembly of the European Geophysical Society held at Nice in April 2000, representatives of about eleven EMIC modeling groups described the details of the components that made up each EMIC. It was decided to design a template which will give for each EMIC its scope, the model components and performance, and selected applications. At the end of August 2000, two EMICs from Belgium (models 4, 8, see Table 1), two from Canada (models 6,10), two from Germany (models 2, 9), and one each from the Netherlands (model 3), Russia (model 5), Switzerland (model 1) and the USA (model 7) were included in a Table of EMICs. (model 11 was added in December 2000.) The table is available to the public on internet via http://www.pik-potsdam.de/data/emic/table_of_emics.pdf. A brief summary of the table of EMICs is given in Table 2. It will be updated whenever there are new entries, either as updates of the models already included or as new contributions. Therefore, the reader is encouraged to contact the lead author of this paper if his/her model is missing in the table of EMICs.

Here we would like to present an analysis of the table of EMICs to provide an overview of the broad spectrum of EMICs, and to describe their approximate location in the new spectrum of climate system models suggested above in Fig. 1.

Table 1. References to EMICs

Model	Short list of references
1: Bern 2.5D	Stocker et al. (1992), Marchal et al. (1998)
2: CLIMBER-2	Petoukhov et al. (2000), Ganopolski et al. (2000)
3: EcBilt	Opsteegh et al. (1998)
4: EcBilt-CLIO	Goosse et al. (2000)
5: IAP RAS	Petoukhov et al. (1998), Handorf et al. (1999), Mokhov et al. (2000)
6: MPM	Wang and Mysak (2000), Mysak and Wang (2000)
7: MIT	Prinn et al. (1999), Kamenkovich et al. (2000)
8: MoBidiC	Crucifix et al. (2000a)(2000b)
9: PUMA	Fraedrich et al. (1998), Maier-Reimer et al. (1993)
10: Uvic	Weaver et al. (2000)
11: IMAGE 2	Alcamo (1994), Alcamo et al. (1996)

4.1 Scope of EMICs

EMICs are designed for a broad spectrum of purposes. Some deal with quite general studies of feedbacks within the climate system for the past, the present and future scenarios on time scales of 10^2 to 10^5 years (models 2, 6, 8). Some focus more on atmosphere-ocean-vegetation dynamics in the mid and high latitudes (models 3, 4) or globally (model 9) on time scales ranging from synoptic to millennial, and others focus on the role of the large-scale thermohaline circulation in the climate system on time scales of 10 to 10^3 years (model 10) and far beyond (model 1). Model 5 addresses the problem of decadal climate variability at mid latitudes, and models 7 and 11 are specifically designed for simulations with respect to the problem of global change. The latter models also include socio-economic components, and therefore they come closest to a complete Earth system model, i.e., a model in which the anthroposphere is included in some interactive way, rather than being included through a prescribed boundary condition.

4.2 Location of EMICs in the spectrum of climate system models

To determine the approximate location of EMICs in the spectrum of climate system models depicted above, we identify the vertical coordinate *integration* (I) with the number of interacting components of the climate system explicitly described in a model. All models in the table of EMICs encompass an atmospheric module and an ocean module including a sea-ice module. The atmospheric modules are labeled as EMBM: energy and moisture balance models, DEMBM: energy and moisture balance models including some dynamics, SDM: statistical dynamical models, QG: quasi-geostrophic models, and GCM: general circulation models. Atmospheric chemistry is included only in models 7 and 11. The horizontal resolution of atmospheric modules is given explicitly. In the case of a spectral model, the truncation (e.g., T21) is

Table 2. Interactive components of the climate system being implemented into EMICs (for explanation see text)

Model	Atmosphere	Ocean	Biosphere	Sea ice	Inland ice
1	EMBM, 1-D(φ)	2-D(φ, z), 3 basins	B_o, B_T	T	
2	SDM, 2-D(φ, λ)-mL	2-D(φ, z) 3 basins	B_o, B_T, B_V	TD	3-D, polythermal
3	QG, 3-D, T21, L3	3-D, 5.6°×5.6°, L12		T	
4	QG, 3-D, T21-L3	3-D, 3°×3°	B_T, B_V	TD	
5	SDM, 3-D 4.5°×6°, L8	SDM, 2-D(φ, λ) 4.5°×6°, L3 fixed salinity		T	
6	EMBM, 1-D(φ), land/ocean boxes	2-D(φ, z), 3 basins		TD	2-D(φ, z), isothermal
7	SDM, 2-D(φ, z)/atmospheric chemistry	3-D, 4°×1.25° to 3.75°, L15	B_T	T	
8	QG, 2-D(φ, z)-L2	2-D(φ, z), 3 basins	B_o, B_T, B_V	TD	2-D(φ, z), isothermal
9	GCM, 3-D, T21, L5	3-D, 5°×5°, L11	B_o	TD	
10	DEMBM, 2-D(φ, λ)	3-D, 3.6°×1.8°, L 19		TD	3-D, polythermal
11	DEMBM, 2-D(φ, λ)/atmospheric chemistry	2-D(φ, z), 2 basins	B_o, B_T, B_V	T	

indicated. Ln refers to the number n of vertical layers. Details can be found in the original literature cited in the table of EMICs.

Ocean modules can be divided into fully three-dimensional oceanic circulation models (labelled as 3-D in Table 2) and variants on the zonally-averaged formulation. Nearly all two-dimensional ocean models labelled 2-D(φ, z) represent the world ocean by three two-dimensional boxes (Pacific, Atlantic, Indian oceans) which are coupled zonally where meridional boundaries do not exist. An exception is model 11 which represents the world ocean with two-dimensional models of both the Indo-Pacific Ocean and the Atlantic Ocean joined by the Antarctic Circumpolar Ocean. Sea-ice modules are separated into thermodynamic models (T) and thermodynamic models which include advection and/or sea-ice dynamics (TD).

All models compute the mass balance of snow on the continents in some way. We consider, however, a module of inland ice sheets as interactive module only if ice flow dynamics is described. The dimension of the ice flow model is indicated. Two inland-ice modules, labeled as polythermal, explicitly simulate the thermodynamics of ice sheets.

With respect to biospheric modules, some models include terrestrial carbon pools, others marine and terrestrial carbon pools, thereby allowing closure of the global carbon cycle, and a third group of models also describe global vegetation dynamics. (Model 11 also describes global land cover changes due to anthropogenic influences.) Therefore, we decided to specify the biospheric modules as B_O and B_T, which refer to oceanic and terrestrial carbon dynamics, respectively, and B_V, which refers to vegetation dynamics.

We now quantify the coordinate *integration* in Fig. 1 by counting the number of interactive components explicitly described in a model. This tends to overemphasize inclusion of biospheric components. We did this on purpose in order to underline the important role of a closed carbon cycle in the natural Earth system. However, a slightly different specification will not change the results of our analysis qualitatively.

The *processes* coordinate in Fig. 1 is a measure of the number of processes described in a model. This number is hard to evaluate. One could, for example, take the number of prognostic and/or diagnostic equations. However, this brings about the problem of specifying a process. Should, for example, the variation of near-surface heat fluxes with atmospheric stability, commonly parametrized by using a simple stability function, be considered a process? In view of these quandaries, we consider the spatial dimension of atmospheric and oceanic modules as a convenient, because easily accessible, indicator of the number of important processes explicitly described in a model. For example, a two-dimensional, zonally averaged atmospheric model [indicated as 2-D(φ, λ) or 2-D(φ, z) in Table 2] commonly parametrizes synoptic processes in terms of some large-scale diffusion. Likewise, a zonally averaged oceanic model does not explicitly resolve wind-driven gyres or phenomena like the El Niño-Southern Oscillation. Hence these models treat processes of major importance in the climate system in a completely different way than three-dimensional models of the atmosphere and ocean (labelled 3-D in Table 2). In the case of a zonally averaged oceanic module which encompasses different ocean basins, we specify the dimension as 2.5. Likewise, we allocate the dimension 2.5 to a vertically averaged atmospheric module, if the three-dimensional structure of the atmosphere is diagnosed (indicated as ml = multi layer in Table 2) and is used for the parametrization of clouds or the computation of radiative transfer. Box models, for comparison, are given a dimension of 0.5.

The coordinate *detail of description* in Fig. 1 could be interpreted as the detail of description of processes. In this case, the indicator is very closely related to the mentioned *processes*. Therefore we suggest that the *detail of description* characterizes the degree of geographical details or geographical integrity a model can potentially capture. To avoid a linear correlation of *integration* and *detail of description* we have chosen to estimate only the number of grid points of the atmospheric and oceanic modules, but not of the other modules. In many cases, the spatial resolution of vegetation models or models of marine biosphere coincides with the resolution of the atmospheric models or ocean models, respectively. (There are exceptions to this rule. Model 2 uses a dynamic ice-sheet module at a much higher resolution than the atmospheric module, and in model 11, the biosphere is described with two orders of magnitude more spatial units than the atmosphere and ocean combined. In these cases internal downscaling methods are used to bridge the gaps between spatial scales.)

Given this definition, *detail of description* differs from *integration* and *processes*. Commonly, modelers choose a proper balance between spatial resolution, i.e., *detail of description*, and the type and number of processes to be explicitly modeled. For several purposes, however, one could imagine a simple energy balance model to be run on a fine grid. Perhaps this model draws a fairly accurate picture of areally distributed heating of the near-surface atmosphere. As energy balance models commonly describe large-scale energy transport in the atmosphere by a simple model of heat diffusion they cannot realistically represent atmospheric processes smaller than a typical mixing length. The latter is given by the typical horizontal extent of weather systems, i.e., of the order of 10^6-10^7 m. Hence there is a mismatch between *detail of description* and number of *processes* described in a model, which, however, could be perfectly sensible for some applications.

Given these specifications, we are now able to determine the position of EMICs in the spectrum of climate system models (see Fig. 3). It becomes apparent there is a broad range of EMICs. Tentatively, all EMICs can be divided into three larger groups: models 3, 4, 9 are simplified comprehensive models. They were derived from fully three-dimensional models, but with a coarser spatial resolution than the current comprehensive models and a simplified parametrization package. They are designed for studying climate variability on decadal and century time scales; therefore, they have to properly describe, not just to parametrize, the mechanisms of large-scale transport. Six of the EMICs (models 1, 2, 5, 6, 8, 11) conceptually differ from simplified comprehensive models. There, comprehensiveness is deliberately sacrificed for the sake of *integration*. Two models (models 7 and 10) do not precisely fit into these defined categories. Model 7 is derived from comprehensive models of the atmosphere and ocean. However, it uses a simple, box-like geometry of the oceans, and it has a zonally averaged atmosphere. Model 10 encompasses comprehensive ocean, sea ice, and land-ice subcomponent models, but with a simplified surface energy/moisture balance atmosphere model with parametrized dynamical feedbacks.

For comparison, we included in Fig. 3 a "typical" box model in which the atmosphere, ocean, and vegetation are represented in a number of, of the order of ten, boxes. According to our specification of *processes* in terms of a cumulative dimension D, they are assigned D = 1. Comprehensive models are also depicted as AGCMs (atmospheric general circulation models), AO-GCMs (atmosphere-ocean-sea ice models), and CSMs (climate system models). The latter encompasses biospheric modules (e.g., Cox et al. 2000).

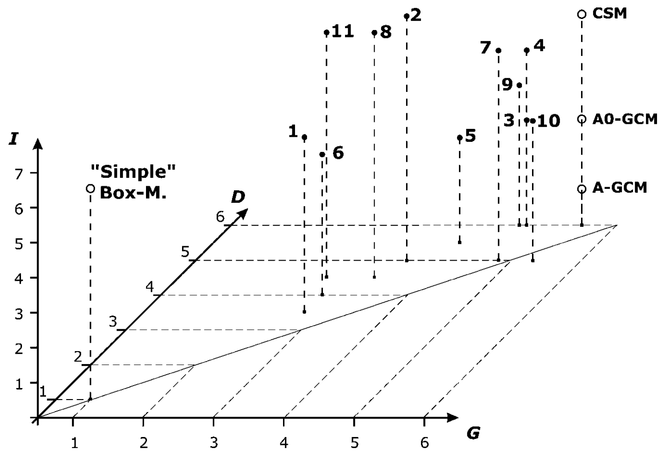

Fig. 3 Location of various models in the spectrum of models of the natural Earth system. The coordinates are: *I*, number of interacting components of the climate system explicitly described in a model; *G*, order of magnitude of the number of grid cells when counting atmosphere and ocean modules only; *D*, cumulative dimension, i.e., spatial dimension of the atmospheric and of the oceanic modules. The *numbers* refer to model numbers listed in Table 1

5 Conclusion

Definition of climate in terms of the state and statistics of the climate system components is now commonly accepted, at least in the community of climate modelers. Because of the broad spectrum of typical time scales of the different components of the climate system, simulation of climate system dynamics requires different types of models. The classical pyramid of climate models proposed by, e.g., Henderson-Sellers and McGuffie (1987, see also the 2nd edition McGuffie and Henderson-Sellers, 1997), does not reflect this aspect, and it appears to be biased towards comprehensive models of atmospheric and oceanic circulation. Therefore, we have suggested replacing the hierarchy by a spectrum of climate system models which explicitly includes an indicator, known as integration, which characterizes the number of interacting components of the climate system being explicitly described by a model.

The location of various climate models in the spectrum has been discussed. In particular, the location of the Earth system models of intermediate complexity (EMICs) has been determined. Figure 3 reveals that there is a broad range of EMICs reflecting the differences in scope. In some EMICs, the number of processes and the detail of description is reduced for the sake of enhancing integration, i.e., the simulation of feedbacks between as many components of the climate system as feasible. Others, with a lesser degree of integration, are used for long-term ensemble simulations to study specific aspects of climate variability. There does not seem to exist a big gap between EMICs and CGCMs. Indeed, some of the more comprehensive EMICs are derived from CGCMs. On the other hand, EMICs and conceptual or simple models differ much more. This interpretation is not just a matter of perspective from which Fig. 3 is drawn. It reflects the notion that EMICs as well as CGCMs tend to preserve the geographical integrity of the Earth system, which is certainly not the case in conceptual models. Furthermore, in simple models being used in the IPCC (Intergovernmental Panel on Climate Change, Houghton et al. 1997) projections, the climate sensitivity is prescribed. Most EMICs, except for model 1, compute sensitivity, just as CGCMs do.

Generally, we argue that there is a clear advantage in having available a spectrum of climate system models. Most EMICs are specifically designed for long-term simulations over many millennia, and some are designed to simulate the interaction of as many components of the climate system as possible in an efficient manner. Moreover, EMICs can explore the parameter space with some completeness. Thus, they are more suitable for assessing uncertainty, which CGCMs can do to a significantly lesser extent. On the other hand, it would not be sensible to apply an EMIC to studies which require high spatial resolution. EMICs can also be used to screen the phase space of climate or the history of climate to identify interesting time slices, thereby providing guidance for more detailed investigations to be undertaken by CGCMs. For the interpretation of model results, however, conceptual models appear to be very useful (e.g., Brovkin et al. 1998).

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