Development of user-friendly didactic climate models for teaching and learning purposes

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Abstract— This study reports on the development and application of two e-learning tools dedicated to climate science: these are Energy Balance Models, or EBMs. Such physicallybased models form the ideal framework for studying fundamental energy processes at the basis of global climate and climate changes. The main assumption behind this development is that learning strategy would enhance the student's conceptual understanding from improved pedagogical technologies by allowing a greater interactivity and faster turn around, thus allowing a large number of experiments per unit time where all features are interfaced to appealing graphic displays. Consequently, these tools would contribute to learning efficiency. An analysis of the sort of reception such tools obtained in the student community in terms of their structural and overall desian. ergonomy learning performances was carried out. The results show that their understanding of basic climate concepts may improve due to the interactivity and the graphic interfaces, allowing a visual display of the basic climate processes driving the energy balance of the Earth.

Index Terms—*climate models, computer simulations, higher education, learning tools, Fortran, Java, JSP*

1. INTRODUCTION

The theoretical concepts fundamental to climate and climate change are taught at the bachelor level in a number of science departments (e.g., Geography) around the world. As is often the case, undergraduates do not have a profound knowledge of energy flow in the global climate system, and many of them are still having problems understanding the Earth's greenhouse effect, its anthropogenic disruption and the potential links to climatic change. Moreover, lecturers are expected to deal with a broad spectrum of student ability and background [1]. Courses and teaching methods require constant improvement and must also be adjusted to deal with classes having wider objectives. Recently, a growing interest in computer-based e-learning tools has prompted the development of innovative learning strategies [e.g., 2]. One of them is provided by web-based applications for climate processes. Nowadays, only a few, scattered and more-or-less user-friendly options with graphic interfaces exist to facilitate learning and better understanding of the complexity of the climate system. For example, in Java [3,4,5,6]; others present the many steps needed to achieve a climate model by means of Matlab [7,8] or with the Stella environment [9]. More complex software, allowing students to learn and experience the full climate system are available on the web [EdGCM; 10]; their use is, as yet, restricted to graduate students and people having the necessary scientific background, and form excellent methods for those who need to have a comprehensive knowledge of the climate system. Learning with increasingly innovative pedagogic methods may turn out to be more beneficial for learners than plugging numbers into memorized equations for which no connection to the real world exists, such as is the case in a classical teaching environment. Nowadays, computer simulations and virtual labs are becoming efficient tools for learning [11,12]. Traditional pedagogical supports such as blackboards, textbooks, transparencies and videos have been complemented by computerbased e-learning tools, allowing teaching to take place in a more polyvalent, ordered and appealing educational environment. Such new technologies are not intended to replace lecturers, however. The latter, rather than having to change their roles, may be less focused on teaching theoretical aspects of climate science and should concentrate more on the learning strategies to be adopted by the students, who would feel more involved in their training.

The goal of this study is to develop and apply a number of simple climate model interfaces aiming to improve teaching of climate and climate change concepts. In addition, these would help learning of climate processes by interacting with an easy-to-use interface, thus allowing fast turnaround experiments. One main advantage is that these interfaces can be used remotely, outside the lecture theatre, thus helping to optimise the

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absorption of climate concepts by students wherever computers connected to external networks are available. In the following study, an e-learning method is described, forming userfriendly didactic climate models for teaching and learning purposes. This is currently done by interfacing Fortran programs, using input files with Java script, thus allowing learners to interact easily by means of sliders and boxes where parameter values can be modified, and thus provide an appreciation of the results by means of an attractive built-in graphic interface. A number of students have been requested to evaluate these model interfaces, and the results have been compiled and analysed in order to give some credit to this method.

2. SIMPLE ZERO- AND ONE DIMENSIONAL ENERGY BALANCE CLIMATE MODELS

Modelling of the Earth's energy balance is founded upon physically-based calculations of the greenhouse effect. Such studies began when Joseph Fourier [13] explained that the atmosphere retains heat radiation. The energy budget then started with bulk calculations for the energy balance of the whole planet, as if it were a rock hanging in front of a fire. Tyndall [14] discovered that certain gases, such as water vapour and carbon dioxide (CO₂) are opaque to infrared rays, thus helping to keep our planet warm by preventing this radiation from escaping into outer space. Arrhenius [15] then developed calculations of the radiation transfer for atmospheres with differing amounts of CO₂ and speculated that changes could have caused Ice Ages and interglacial periods. Later, after continued theoretical and empirical work on the embryonic climate-change theory induced by variations of the concentration of greenhouse gases [e.g., 16, 17, 18, 19], the advent of digital computers helped to perform extended calculations of infrared absorption in the atmosphere [20, 21], revealing that significant climate changes were effectively plausible. It also became obvious that feedback had to be taken into account in order for the calculations to be considered realistic. The structures that scientists tried to build upon these findings may be called "models" and their first application was to explain the world's climates and their variation. Budyko [22] computed the balance of incoming and outgoing radiation energy according to latitude, and found that the heat balance worked very differently in high latitudes compared to those of low latitudes. Soon after, Sellers [23] built on these ideas and computed possible variations of the actual atmosphere separately for each latitude zone. Consequently, the theory that increasing industrial activities may eventually lead to a global climate much warmer than today has been corroborated. These thought-provoking

results fostered interest in simple models where they served as a helpful starting point for testing a number of assumptions. Energy Balance Models (EBMs) of this type, although simple, remain interesting tools for studying global climate and climatic change [e.g., 24]. They may thus be considered as valuable virtual laboratories for modern students. These "simple" models that run on desktop computers were comparable to those that had been considered state-of-the-art for the most advanced computations in the 1960s. A brief overview of the theoretical background used to build these models follows. The equilibrium between absorbed solar and emitted infrared radiation forms the first approximation to a model of the Earth's global climate. The version proposed in this project can be run through a user-friendly web page where a number of sliders can be used to modify parameter values. Stepby-step calculations are not revealed, but final results are displayed on the screen so that users can modify the displayed plots. These can be executed quite rapidly on desktop computers connected to a local network by establishing a connection to a server equipped with Java facilities [JSP; e.g., 25, 26], and where users can

interact and visualise two EBMs (driven by Fortran programs) through sophisticated visual graphic displays (provided by Java scripts).

2.1 Description of the EBM 0D

This climate model may be used to numerically simulate and display the mean temperature of the global Earth-Atmosphere system, represented by a single point in space under the influence of absorbed solar and emitted infrared radiation [27; Chap. 10]. The temperature, *T*, evolves to a constant value after the equilibrium between the absorbed solar energy and the outgoing thermal infrared energy is reached, as follows:

$$D_{\rm m} C \frac{{\rm d}T}{{\rm d}t} = \frac{F_{\rm s} I_{\rm o}}{4} \left(1 - \alpha_{\rm p}\right) - \tau_{\rm a} \varepsilon \sigma T^4 \qquad (1)$$

where I_{o} represents the solar constant (1370 W m⁻²) and α_p is the planetary albedo determining the solar absorption. All the parameter values are displayed in Table 1 of the Appendix. The time- and space-averaged energy input rate is therefore I_0 / 4 over the whole Earth and the reflection is given by $I_0 \alpha_p / 4$. A rheostat, $F_{\rm s}$, is introduced in order to change the solar power input. The surface may be considered as a blackbody in the infrared so that the infrared emissivity ε , may be taken as unity. The atmospheric transmissivity in the infrared is τ_{a} , and σ is the Stefan-Boltzmann constant (5.67 x 10⁻⁸ W m⁻² K⁻⁴); consequently the infrared loss is a function of the fourth power of the system temperature. The thermal inertia is controlled by C, the volumetric heat capacity of the system (J m⁻³ K⁻¹), mainly sea water, and $D_{\rm m}$

is the ocean mixed layer depth (m). A finite difference equation used to simulate the temperature evolution may be written in the form:

$$T_{n} = T_{n-1} + \frac{\Delta t}{D_{m}C} \left[\frac{F_{s}I_{o}}{4} \left(1 - \alpha_{p} \right) - \tau_{a}\varepsilon \sigma T_{n-1}^{4} \right]$$
(2)

where iterations noted by integer values $n \in [1, 1]$ 2, ..., N], are achieved with a timestep Δt , here equal to one day, starting at 0 with T_{o} as the initial temperature followed by T_1 after Δt , etc., ending at T_N after N Δt (50 years). Under normal conditions, the equilibrium temperature is reached before the Nth iteration. In this version of the model, sliders allow users to modify the default parameter values of { T_{o} , α_{p} , τ_{a} , F_{s} , D_{m} } equal to {200 K, 30 %, 62 %, 1, 20 m} respectively (Fig. 1), producing an equilibrium temperature of 287.4 K (~14.2°C). If one or more values are modified, the rate of change and the equilibrium system temperature are also modified as shown by the different curves in Fig. 1. The parameters can be modified within reasonable values determined by each slider. One or more parameters may be changed simultaneously in order to visualise and therefore to understand the respective roles played by radiation and the thermal characteristics of the climate system with respect to global average temperature evolution.



Figure 1. Planetary Energy Balance Model I (EBM 0D) home page. This interface allows the user to choose different parameter values and up to three experimental curves can be displayed on the orthogonal axis {Temperature (in K) vs Time (in years)} shown above. This page also hosts a number of documents available to the users, such as a user's guide, an overview as well as a reference manual for experiments.

2.2 Description of the EBM 1 D

If the surface of the Earth is partitioned into a fixed number of latitudes and the energy balance principle is applied, a one-dimensional climate model is thus developed [e.g., 27; Chap 10]. It computes the zonal average surface air temperature distribution from the Equator northward as a function of the absorbed solar radiation, the emitted infrared and the meridional heat transport at a given latitude according to the ideas of Budyko [22] and Sellers [23]. Assuming a zonal thermal equilibrium, and considering each zone separately, the formulation of this simple steady-state EBM 1D may be written as follows:

$$\boldsymbol{K}_{j}^{\downarrow} \left(1 - \alpha_{j} \right) = \boldsymbol{L}_{j}^{\uparrow} + T\boldsymbol{r}_{j} \tag{3}$$

In this application, $\kappa_j^{\downarrow} = K_{\downarrow}(\varphi_j)$ represents the downwelling incident solar radiation at latitude φ_j , $\alpha_j = \alpha(T_j)$ is albedo computed as a function of zonal temperature in zone φ_j , $L_j^{\uparrow} = L_{\uparrow}(T_j)$ is the zonal average infrared loss at latitude φ_j , and $Tr_j = Tr(T_j)$ is the rate of transport of energy in/out latitude φ_j by the combined atmospheric and oceanic circulations. Here, $T_j = T(\varphi_j)$, represents the steady-state zonal-average temperature at latitude φ_j , j = 1, 9. In order to resolve Eq. (3) analytically, the infrared loss and the rate of transport of energy may be linearized as follows [24; Chap 3]:

$$L_{i}^{\uparrow} = A + B T_{i}$$
(4)

where *A* and *B* are empirical parameters whose values account for the greenhouse gas concentration in the atmosphere, and the heat transport is parameterised as a heat diffusion process as follows:

$$T_{r_{j}} = \mathcal{K} \left(T_{j} - \overline{T} \right)$$
(5)

where \overline{T} represents the globally-averaged temperature. The surface albedo can be parameterised by a step function as:

$$\alpha_{j} = \begin{cases} = 0.6 & \text{when } T_{j} \leq T_{\text{crit}} \\ = 0.3 & \text{when } T_{j} > T_{\text{crit}} \end{cases}$$
(6)

which represents the albedo increasing at the snowline where T_{crit} , is a critical temperature whose typical values are between -10°C and 0°C. By combining Eqs. (4), (5) and (6) into Eq. (3) and rearranging it, one can obtain the following solution for the steady-state zonal-average temperature:

$$T_{j} = \frac{K_{j}^{\downarrow} (1 - \alpha_{j}) + K\overline{T} - A}{B + K}$$
(7)

In this version of the model, individual sliders can be used to vary one or many parameter values within a range of reasonable values determined by each slider (Fig. 2). The effective albedo is a function of the surface albedo, $\alpha_{\rm sfc}$, of the cloud, $\alpha_{\rm clouds}$, and of the ice, $\alpha_{\rm ice}$. The longwave parameters *A* and *B* are set to 204 W m⁻² and 2.17 W m⁻² °C⁻¹, values first devised by Budyko [22]. After a few seconds of computations using default parameter values, it computes and displays zonal–averaged quantities such as temperature, absorbed solar energy flux, emitted infrared energy flux, etc. One or more parameters may be changed simultaneously in order to understand and visualise on the maps generated the respective roles played by radiation and thermal characteristics of the climate system with respect to global average temperature, where the snowline appears directly on these maps as shown in Fig. 2.

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Figure 2. Planetary Energy Balance Model II (EBM 1D) home page. This interface allows the user to choose different parameter values, and different maps can be displayed at the top of this page. The page also hosts a number of documents available to the users, such as a user's guide, an overview and a reference manual for experiments as well.

3. MODEL EVALUATION BY A SAMPLE OF LEARNERS

To undertake a combined qualitative and quantitative assessment of these model interfaces, a sample of M. Sc. students was prompted to make a survey. They were asked to answer a number of questions regarding the models' formal (visual display, graphic) in relation to their structural (functions, parameters, sliders) aspects; also taken into consideration were their essential values as a learning tool, and ultimately to their usefulness by employing the models to perform simple tests and applications in response to meaningfully prepared assignments. Individual answers were then compiled and analysed in the context of the e-learning environment to verify if these simulators met certain learning requirements and if they were bringing added value to the teaching environment.

3.1 Method

A number of students, studying Physical as well as Human Geography, were gathered in a room and equipped with enough computers for them to participate in this survey individually. The background of these students was very heterogeneous and not all of them had a solid scientific basis. The two model interfaces were directly available on-line. A questionnaire was distributed to all and a period of one and a half hours was allowed to go through it so as to obtain meaningful and detailed answers. In order to facilitate the compilation of all of the replies, students were asked to complete a document that was included in a Learning Management Environment (MOODLE), so that the textual portion of the answers could be illustrated by graphs copied and pasted directly from the simulator web page into this document. A short theoretical overview of the models had been provided prior to the evaluation. The first part of the assessment concerned formal aspects of the simulators regarding their overall visual aspects and their display features such as the use of sliders to change parameter values and graphic outputs; these were set up to test if the climate simulators were visually appealing or not. Other important questions concerned the usage (how often) and the time spent (how long) on each of the climate simulators. The second part of the assessment was aimed at general learning objectives. What were the most significant processes that the students had understood better, updated, or had been revealed to them using these models? Some more targeted questions were asked, for instance. How it showed that the inertia of the Earth's climate system influences the time to reach thermal equilibrium? Does the thermal inertia depend upon the initial temperature? What is the decrease of the solar energy necessary to produce an ice-covered Earth? What is the role of infrared transmissivity (a function of the greenhouse gas concentration in the atmosphere) on the maintenance of the Earth's surface temperature? What happens if the greenhouse gas concentration increases? What

is the role of meridional heat transport in the maintenance of zonal climates? With carefully chosen 1D EBM parameters, are the many results simulated by the 0D EBM reproduced exactly? How? etc.

3.2 Results

Ten guestionnaires were returned after the survey. The compilation of the results indicate that all of the students considered that the simulators are visually appealing, and that their setup and objectives were satisfactory; i.e., simulating global-averaged temperature for the first (EBM 0D) and zonal-averaged temperatures for the second (EBM 1D). All of them mentioned that the structural organisation, sliders and the graph position were quite satisfactory. However, many of them proposed that online definitions of all of the parameters and functions should be available when the mouse-pointer encounters appropriate locations. All of them used the simulators several times during their learning phase (e.g., prior to this evaluation), and spent between fifteen minutes and an hour on it; they spent thirty minutes on average each time they logged on. When using these climate simulators, they also learned more about useful concepts, such as the order of magnitude of changes and model sensitivity, thanks to the sliders and to the graphic displays. An example is related to the thermal inertia of the earth, mainly controlled by the product $(D_m C)$, as a determiner of the time needed to reach the global thermal equilibrium. This temperature is computed on the basis of Eq. (1) in which dT/dt = 0, i.e., when the absorbed solar energy is equal to the infrared lost, and it follows that:

$$T_{eq} = \sqrt[4]{\frac{F_{s} I_{o} (1 - \alpha_{p})}{4 \tau_{a} \varepsilon \sigma}}$$
(8)

This temperature is independent of the thermal inertia. Given the same initial temperature (cold start at 200 K) the differences are greatest after



Figure 3. By using EMB 0D many users appreciated how long it took to reach thermal equilibrium and finally understood the meaning of the value of the steady state temperature.

two years, and it takes forty years for both experiments to converge to within 0.1 K when the inertia is multiplied by ten, as shown in Fig. 3. They found that the global average temperature is rather sensitive to infrared transmissivity τ_a . An important feature, related to this value, is that without an atmosphere i.e., $\tau_a = 1$, $T_{eq} = 255$ K (-18°C). The presence of greenhouse gases, such as water vapour, CO₂, CH₄ and N₂O in an atmosphere will decrease the infrared transmissivity and consequently trap heat in the lower atmosphere.

They found that $\Delta \tau_a$ = -3.2 %, with τ_a decreasing from .62 to 0.60, which is roughly what is needed to simulate the effect of enhanced infrared trapping by doubling the CO₂ concentration in the air, produced a ΔT_{eq} = +2.4°C increase in global average temperature. This is a realistic prognosis for future climatic change that will occur during the course of the XXI^e Century. Also, an important feature of the behaviour of these simple climate models that the learners understood well is that an Ice Age can be easily simulated by decreasing the value of the solar constant. The global average temperature reached the equilibrium value of 273 K by changing the value of the solar constant by roughly ΔI_0 = -19%. During theoretical lectures, they learned that meridional heat transport is induced by the energy deficit that exists between the Equator and the Poles. With the EBM 1D, it was obvious that reducing or increasing the heat diffusion coefficient K, by 10% produced a larger or a smaller North–South temperature gradient - as large as 3.7°C at the Poles and as small as 1.5°C at the Equator - but at the same time leaving the global average temperature unchanged. This is not so obvious, since the heat transport coefficient appears in both the numerator and the denominator in Eq. (7). There was a better understanding that reduction of K further acts as a decoupler for these two zones, i.e., the former getting hotter and the latter colder respectively, as shown in Fig. 4 for a 5% decrease of K. The students had been asked to emulate the increase in the greenhouse gas in the atmosphere by properly "tuning" the infrared parameters A and B. They soon found that the zonal temperatures are very sensitive to these. An increase of zonal temperatures can be simulated by decreasing the parameter B, that is decreasing further the infrared loss to space when temperature is increasing. In order to simulate an Ice Age, a similar decrease of the solar constant is needed, such as $\Delta I_{\rm o}$ = -19%, where the former is defined in this context as an Earth and where the ice margin reaches the Equator.

3.3 Discussion

All the participants agreed that the conceptual aspects at the basis of a particular mathematical

model complemented by visual support aided a better understanding of climate and climate change. They also agreed that the theoretical lectures are essential prior to using these elearning tools. The participants were also in agreement when they pointed out that one drawback following the use of such a tool is that it may not be conducive to further study, and to a feeling by learners that climate science is trivial and straightforward. This is one reason why these tools must be used as a complement to the theory, not as a surrogate for climate science.

To provide an example of this word of caution, we might mention that these models are generating a number of "raw" results which need to be analysed further. In that respect, learners were asked to appreciate the so-called "backward" consistency of the results. In particular, the EBM 1D results, when properly diagnosed, may be compared directly with those of the EBM 0D when the model input parameters are "similar". A comparison is made between the zonal averaged temperatures and the global average, where the former are averaged with weights proportional to the cosine of the latitude $\cos \phi \Delta \phi$. For example, when default parameters are used, the global average temperature simulated with the EBM 0D, gives 14.2°C compared with the 15.0°C of the EBM 1D. This difference, in simulated temperatures attributed to the different model parameterisations, is not deemed significant. The same diagnostics apply for the absorbed solar and the infrared lost to space, and also give comparable results with both models in the order of $235 \pm 5 \text{ W m}^{-2}$.



Figure 4. By using EBM 1D users found that decreasing the meridional heat transport coefficient by 5% decouples the Equator and the Poles, i.e., the Equator warms and the Poles cool by 0.5° C and -1° C respectively, but the global average remains unchanged.

A number of climatic aspects have not been considered here, such as a more complete sensitivity study of the Earth's global temperature relating to the variation of different parameters of the model: these include the amount of cloud, the surface albedo, etc., but this is well beyond the scope of the present study. Nevertheless, one important aspect they found is that, despite the relative success of these two EBMs to simulate general aspects of the thermal structure of the Earth, the models have limitations. Indeed, the geographical distribution of the temperatures is not represented, and neither is the vertical thermal structure. Consequently, they also considered that. to obtain а deeper understanding and analysis of the Earth's climate, one would have to use more complex modelling systems, such as Radiative-Convective models (RC), Global Climate Models (GCM) or the more detailed Regional Climate Models (RCM).

4. CONCLUDING REMARKS

The development of computer-based elearning climate model interfaces has been outlined in this paper. They are mostly dedicated to learning strategies for undergraduates, but may also be used by graduate students and others having to deal with the basics of climate science. An evaluation of two of these tools has been performed where a survey put emphasis on their usefulness, ease of use (ergonomy), added learning values, and on the guality of the graphic displays, thus helping to better absorb and understand the theory. The analysis of the survey indicates that the students are keen to use new technologies, and the added value of such pedagogic tools proved significant. With respect to the learning problems mentioned in the introduction, the analysis of the student comments concerning the quality of these climate model interfaces leads us to the conclusion that, by complementing the learning context with appropriate tools, students may absorb information more easily. We believe this justifies the development of such e-learning technologies where a more complete toolbox using similar "models" is definitely needed. This study is the first phase of a larger project to develop a much wider climate-oriented toolbox. A computerbased virtual learning laboratory similar to the enquiry-based facility in Physics [28] is also envisaged, which will include a set of virtual laboratory-based modules (e.g., models) that will provide a step-by-step introduction to climate science. Through the study of simple climate systems and their interaction, it is presumed that students would gain a better understanding of the fundamental processes controlling the climatic system. Along the lines described above, a global radiative-convective model (RC), based on the same system (i.e., Fortran + Javascript application), is currently under development according to the model equations set out in Chap 10 of [27] and those in Chap. 4 of [24]. This model will allow a deeper understanding of the role played by atmospheric greenhouse gas on the atmospheric temperature profile and thus on the thermal equilibrium of the Earth using an interface similar to that developed so far. One of the big challenges we are facing is to maintain and improve the quality of education on one hand and of the learning on the other in order to draw a large number of students keen on learning

climate science in an appropriate manner so that they gain a useful understanding needed later for research in other activities. E-learning resources provide a quantity of innovative methods, and in this study we have demonstrated to some extent their potential to develop efficient and useful tools having an indisputable added pedagogical value.

APPENDIX

Table 1. Definitions and ranges of the values of the adjustable parameters of EBM 0D and EBM 1D. Below, NP stands for North Pole and EQ for Equator.

0D EBM	Definitions	Ranges	Default
Parameters			values
To	Initial	150 – 350 K	200 K
	temperature		
αρ	Planetary	0 - 1	0.3
	albedo		
τ _a	Atmospheric	0 - 1	0.62
	transmissivity		
Fs	Rheostat	0.5 – 1	1.0
D _m	Mixed/layer	1 – 200 m	20
1D EBM			
α_{clouds}	Cloud albedo	0 - 1	0.5
$lpha_{\sf ice}$	Ice albedo	0 - 1	0.62
$\alpha_{\rm sfc}$	Surface	0 - 1	.5 (NP), .3,
	albedo		.1, .08, .08,
			.05 (EQ)
T _{crit}	Critical	-15 – +5°C	-10.0°C
	temperature		
К	Heat transport	0 – 50	3.81
	coefficient	W m ⁻² °C ⁻¹	W m ⁻² °C ⁻¹
A	Infrared	150 – 310	204
	parameter	W m⁻²	W m ⁻²
В	Infrared	0 – 20	2.17 W
	parameter	W m ⁻² °C ⁻¹	m ⁻² °C ^{−1}
Fs	Rheostat	0.5 – 1	1.0
Ci	Cloud amount	0 - 1	.52 (NP), .58, .62, .63, .57, .46, .4, .42, .5 (EQ)

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