TEACHING TO MODEL COMPLEX DYNAMIC SYSTEMS IN SECONDARY SCIENCE EDUCATION

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Computer models of complex dynamical systems play a major role in science, as well as in societal debate about issues such as climate change. Therefore, insight in computer models and modelling is an important learning aim in science education. However, in teaching practice it has proven difficult to give modelling an integrated role in the curriculum. We took a design research approach to find more feasible approaches to integrate modelling in the secondary curriculum. We developed a physics course in which students constructed, evaluated and refined computer models of the climate system. Our design objectives were to get the students engaged in their own meaningful modelling processes, while retaining the essential characteristics of a scientific modelling process.

A first design and a revised design were classroom-tested. The design proved feasible, and students and teachers were highly involved. However, we found some critical problems to attain the objectives posed in the design. For example, it was intended that students would experience scientific modelling as a purposeful process. However, misfits between students' expectations and the model's intended purpose easily arose. Furthermore, the amount of guidance proved critical, and in the first design, because of too much guidance, we found students answering questions rather than engaging in their own modelling process. In the second design, this was partly resolved by reducing the amount of guidance, which resulted in more classroom discussions, and in solution approaches being more grounded in students' ideas about how to proceed. Nevertheless, across both cycles, students had little real influence on the process, as teachers tended to leave them little room to evaluate their own ideas and outcomes. Based on the comparative analysis of both designs, we suggest design guidelines to implement meaningful computer modelling activities in the classroom.

INTRODUCTION

Models and modelling play a central role in science, and in societal debate about scientific issues. Therefore, an insight in models and modelling is an important learning aim in secondary science education, not just for aspiring scientists, but also as a preparation for citizenship. More specifically, when discussing issues such as climate change, ecosystem behaviour, or traffic congestion, many arguments rely on predictions derived from computer models, and it would be desirable that participants in such debates at least have a basic understanding of the behaviours of such complex dynamic systems, the uncertainties involved with the modelling of such systems, and the power and limitations of computer models.

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[1] Paper to be presented at the 13th European Conference for Research on Learning and Instruction, August 25 – 29, 2009, Amsterdam, The Netherlands. Corresponding author, now at Universiteit Twente, Faculty of Behavioral Sciences, P.O.Box 217, 7500 AE Enschede. Email: b.j.b.ormel@utwente.nl

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The desired insights are not easily acquired through listening alone, and inquiry modelling has been promoted as a means of expressing ideas and constructing deeper understanding of science content (Van Joolingen, De Jong, Lazonder, Savelsbergh, & Manlove, 2005; Wells, Hestenes, & Swackhammer, 1995; White & Frederiksen, 1998). However, thus far these ends proved hard to attain in teaching practice, as both curriculum materials and teaching practices need to be reformed to achieve this (Windschitl, Thompson, & Braaten, 2007).

Our aim is to advance the pedagogy of modelling complex dynamical systems in secondary education through the development of exemplary teaching approaches. Starting point for the approach was that students need an authentic modelling experience they can reflect on in order to gain the desired insights and skills. Based on the literature (e.g., Maaß, 2006; Vollebregt, 1998), we identified three essential design objectives the modelling experience must meet in order to promote the desired insights:

- the modelling process must retain essential characteristics of a scientific modelling process, such as purposefulness, knowledge-based model design, model evaluation, and progressive model refinements;
- the problem and the steps to take must be insightful for students;
- the problem must leave sufficient room for students to contribute productively.

In a review of recent curriculum development projects on modelling, we found that in most projects one or more of these aspects are missing (Ormel, submitted).

As a proof of existence, and in order to clarify our design guidelines, we developed a course on predicting the global-mean temperature, with the aim to create an authentic modelling experience in the classroom. In twelve lessons, students would construct a series of computer models, and evaluate their models against empirical data.

METHOD AND SAMPLE

Starting from initial ideas about the essence of modelling, tested against literature findings, teaching material was developed in close collaboration with teachers and domain experts. The design was classroom-tested twice as part of regular physics courses.

Four teachers with 65 students altogether, participated in the field test of the first design. The lessons were video-taped, and students' products were collected afterwards. Screen activities of students' model construction activities were captured. The transcribed data were analyzed both inductively and by comparison to scenarios of expected teacher and student behaviour. This evaluation led to a redesign which was field tested in the same way, this time with one of the experienced teachers.

GLOBAL OUTLINE OF THE DESIGN

We had identified general features of the scientific modelling process, such as a model being a purposefully simplified description of reality, which is being adapted iteratively until it serves its intended purpose (Van der Valk, Van Driel, & De Vos, 2007; Wong & Hodson, 2009) In order to make this iterative process happen in the classroom, we had decided to situate the entire series of lessons in a single continuous context. We had further specified the desired features for the specific case of computer-supported dynamic systems modelling. Dynamic systems, such as the climate system, tend to change over time, both through external influences and through their internal dynamics. In order to predict their long term behaviour, it doesn't suffice to extrapolate current trends, but one needs to take into account the underlying causal mechanisms. For many complex systems, predictability of the long term behaviour is limited, first because of practical reasons (limited data, limited understanding of

the mechanisms), but also more inherently, because such systems tend to behave chaotically (i.e. in the long run minor differences in the initial states can lead to very different outcomes). The content aim of the lessons was to recreate a ‘scientific modelling process’ in the classroom that would retain the essential features mentioned above. In order to facilitate students computer modelling activities, we used the graphical system dynamics modelling tool Powersim (cf., Löhner, 2005; Löhner, Van Joolingen, & Savelsbergh, 2003).
A series of twelve lessons was developed in which the students developed a series of models of increasing complexity. Starting from the initial leading question, ‘What will be the global mean temperature in 2200?’, students started with simple quantitative models to account for the current global mean temperature (first the radiation balance model of the earth without atmosphere, and second the same model with an atmosphere added). The second model yields acceptable outcomes, in the sense that the currently observed global mean temperature can be reproduced with the model. Next students moved on to predicting the future. They did some scenario studies, in order to find that the further you extrapolate beyond the data, the more uncertain your prediction becomes. Finally, they modelled the ice-albedo feedback loop (higher temperature lead to less ice, leads to darker surface, leads to more absorption, leads to even higher temperature), to discover how non-linear responses may lead to irreversible changes and how they limit predictability. This latter model is most explicitly a toy model: although all models in this unit are highly simplified, the ice-albedo model is more explicitly a toy model, in that it’s numerical outcomes have no bearings on reality at all, the model just illustrates a mechanism. The lessons were concluded with student presentations and/or report writing.

FINDINGS

Scientific modelling process

During the design process we hit upon the problem that, although the climate system is a prototypical example of a dynamical system, basic climate models, such as the radiation balance model, are equilibrium models in essence. The out-of-equilibrium behaviour of radiation balance models can be computed but, given a lack of suitable parameters, has little quantitative meaning. Even the ice-albedo model does not really describe autonomous dynamic behaviour, but rather a sudden jump between two equilibrium states. It turned out that given the context of climate modelling, within the scope of our twelve lessons, we could hardly advance beyond the groundwork, and truly dynamic model behaviour could not be addressed. Moreover, when we tried to model chaotic systems behaviour for ourselves, we found that the systems dynamics modelling tool we used provided little or no support to detect any but the most evident chaotic behaviours. Therefore, we conclude that in order to address limited predictability as a consequence of chaotic behaviour, we would need to step out of the realistic constraints of climate modelling for a moment, and turn to a prototypical chaotic system that can be addressed at this level.
Moreover, based on the literature, we had set on models being hypotheses about the causal mechanism behind the system behaviour. This turned out to be a too one-sided view: although this may hold true for fundamental physics modelling, climate models turned out to comprise a combination of causal mechanisms and phenomenological relations.

Feasibility

In the first field test, the design proved feasible, and students and teachers were highly involved. With respect to the design objectives, findings were mixed, thus leading to a revised design in the second round. In the following, we highlight some major findings.
Our original design approach was to introduce all the necessary knowledge on a need-to-know basis, within the context of the ongoing modelling process. This worked fine for the required physics background knowledge, but it didn't work for the introduction of differential equations and numerical mathematics. Working with the modelling software was not the problem, but the idea that the time development of a system would be expressed as a set of instantaneous relations, and the idea of computing change over time by taking very small steps turned out to be too alien, and too big to grasp in passing by. As a consequence, in the first field test, many students never became proficient in diagnosing their errors (such as, 'if the outcome approaches infinity, it is likely that your time step is too large'). Therefore, in our redesign we added an introductory module of five lessons about computing radioactive decay. This context was much 'leaner' in the sense that the focus was just on comprehending the computations rather than the entire iterative research process. This worked well for most students.

Insightfulness

The initial drive for the students was to predict a numerical outcome (global mean temperature in 200 years). This is in line with what they are used to in common classroom practice. Later on the emphasis shifted towards qualitative behaviours, and uncertainties. This remained problematic for many students, as the initial purpose of the module, perhaps combined with their classroom experience, led them to keep focusing on quantitative outcomes whereas several 'toy models' were rather intended to provide qualitative insight. Therefore, with regard to the ice-albedo model, they would conclude that the models was worse than its predecessor because it got the temperature wrong. Despite efforts in the revised design to set different aims for the different models, the combination of 'realistic models' and so-called 'toy' models in a single modelling sequence turned out to be problematic, and it might be more advisable to mark a change in model type by changing the context as well.

Each model design phase started from a conceptual discussion, to identify students' ideas and proposed explanations. Student contributions were collected and presented on the whiteboard in informal language and sketches. While the initial classroom discussion would be focused on objects and events, the final model would described relations between quantities. Therefore, the informal object-based model had to be simplified and abstracted step by step,

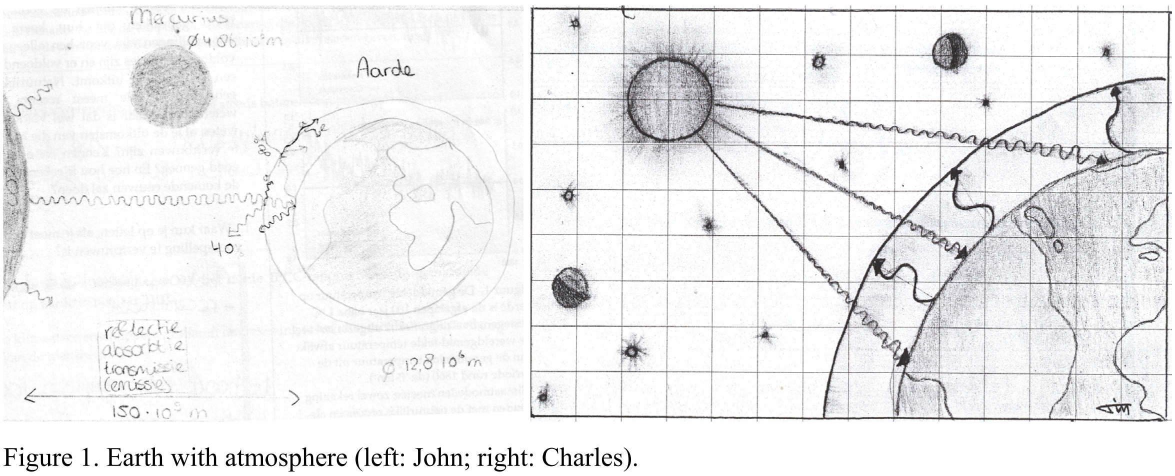

Figure 1. Earth with atmosphere (left: John; right: Charles).

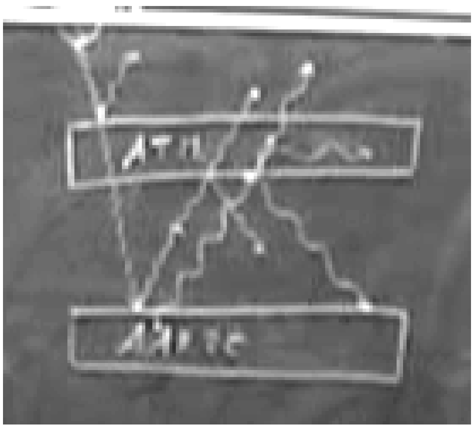

Figure 2. Blackboard with 'scientific' representation by the teacher.

first into a formal diagram, and next into a mathematical model. Especially the transition from informal sketch toward formal diagram proved very hard for both students and teachers. For instance, after a classroom discussion where the mechanism of the greenhouse effect had been discussed and presented in a simplified diagram, students were to make their own drawings (Figure 1). The aim of the activity was that these would be formal diagrams to describe the greenhouse mechanism, but the teacher asked for "a picture, a small sun, a globe with an atmosphere, and a few rays running, and how they cause [sentence stops]". Most students tended to decorate their drawings with irrelevant features. More seriously, several omitted the core part of the mechanism (absorption and reemission of the outgoing radiation by the atmosphere). The drawing on the left does show the essential features, whereas the drawing on the right seems to reflect the common misconception that the atmosphere 'locks in the heat'.

In the next session the teacher announces that they are going to "turn those beautiful paintings into something more scientific on the black board". Without further explanation, he restricts his drawing to a flat piece of earth surface, rather than the entire globe (Figure 2). It had been planned that, in this representation, he would indicate energy flows (with the width of the arrow indicating the magnitude of the flow) thus promoting a discussion about quantities, but he drew ray traces instead. The students fail to see the advantage of this new representation:

1.	Ann	sir, that is not very realistic
2.	Teacher	no, but it is just a model. It is not realistic, we need to simplify
3.	Ann	a model has to be realistic
4.	Teacher	a model has to be realistic
5.	Ann	or it will be entirely
6.	Georgina	or Ann will be confused
7.	Ann	yes, indeed
8.	Josephine	in global outline realistic
9.	Teacher	but now, could you convert your drawing, with all those rays and the sun convert to something like this?
10.	Students	yes
11.	Georgina	I think so, ours will be ok
12.	Harry	yours is such an amateur drawing, sir
13.	Teacher	I will also include the sun. This is the sun, ok? Nicely the right proportions

The teacher completes the 'scientific' drawing, without making it productive to discuss the greenhouse mechanism. Also later on in his teaching, the teacher keeps falling back into object based drawings, where processes and quantities are inserted in a hand waving fashion, thus encouraging the students to do the same. In line with that students find it very hard to come up with strictly 'mechanistic' explanations in terms of rules of change:

1.	Josephine	yes, in fact, the earth heats itself
2.	Georgina	yes, in the end it does, but..
3.	Teacher	it heats itself?
4.	Georgina	no, the earth loses less heat
5.	Josephine	it has a kind of coat around it
6.	Georgina	yes, a coat […].
7.	Josephine	and radiation passes more easily through that coat, compared to how it loses it's heat.

Later on, this 'holistic' explanation of the atmosphere acting as a blanket, remains seductive, although some students are able to give a more precise account:

1.	Researcher	Yes, why could something could like the atmosphere, at 250 degrees Kelvin, heat the Earth?
2.	Edward	There will be extra heat, it causes the extra energy
3.	Research	where is it, the extra..?
4.	Edward	because the sun causes part of the heating anyway
5.	Researcher	yes, yes, of course
6.	Edward	but part of that will be reflected immediately
7.	Researcher	yes
8.	Edward	but the atmosphere absorbs that and radiates part of it back to the earth

In this fragment Edward correctly explains how a cold atmosphere can heat the earth, albeit that he misses the crucial difference between infra red heat radiation, which will be absorbed, and short wave radiation, which will pass the atmosphere unhinderedly.

Once the model has been built, students are to investigate and test their model. For some models this went quite well, as students detected the intended behaviours, and drew the intended conclusions. For instance, with the first model (earth without atmosphere), students found a temperature below the freezing point and they concluded that the model had to be revised. For the ice-albedo model, by contrast, it was intended that students would be surprised by the 'jumping' behaviour of the model, but many failed to see this behaviour because they didn't systematically vary the relevant parameters. If they did find the upward jump, most would still miss the point that the process is irreversible in the sense that the downward jump doesn't occur at the same point were the upward jump occurred. More generally, in order to investigate the responses of your model, you first need an idea of what you are looking for. Whereas scientists tend to know what they are looking for in their models, students don't, and in order to promote more successful model investigations, expectations need to be set beforehand, for instance in the classroom discussion, where the dynamics of a qualitative conceptual model can be 'talked through'.

Opportunities to contribute

In order to provide a workable structure for both students and teachers, the first version of the design was in the form of a work book with detailed step by step assignments and with the required background information provided in text. Although this prevented the inexperienced teachers from getting lost, and it helped to keep the students going, it also turned out that students could just solve the assignments without a clear sense of purpose. Moreover, during classroom discussion students would scroll a few pages forward to find the answers to the discussion. Therefore, in the revised design, the amount of guidance was reduced, with some more advanced physics content being left out, to keep things manageable. Now, the student material presented only general process requirements and background literature, while the specific contents for each phase were to be decided upon in classroom discussions. As expected the teacher gave sufficient room to student contributions, and this led to much more classroom discussion about students' conceptual models. However, if students' ideas diverged, it turned out very hard for the teacher to reach the desired conclusions in a productive classroom discourse, and sometimes the teacher had to impose the required conclusions quite abruptly. Moreover, the teacher's associative style of reasoning led him to disrupt a productive classroom discourse himself, even if the desired conclusion was within reach, such as when the class has to decide on the major source of heat to maintain the earth's surface temperature:

1. Teacher what is the source?
2. Students the sun.
3. Students the inner core of the earth
4. Ismael the core, the magma […]
5. Teacher molten stone, and how could that account for heat…it is …. how old is the earth? 4,6 billion years. A lump of stone, heh? Which hot inside. 4.6 billion years in a very cold surroundings. So it will dot, dot …
6. Students cool down
7. Teacher cool down. It will just cool down, unless…?
8. Students unless it is being heated
9. Georgina by the sun
10. Edward from the outside
11. Students the atmosphere
12. Teacher that is. The heat comes from the outside. Or it must generate it's own heat […]
13. Georgina so, fusion. Nuclear fusion inside the earth.
14. Teacher no, it is too cold for that, but at the inside, not here, but in the magma, there is some radioactive minerals that decay, which causes some heating, but that is only a tiny bit compared to the sun.

The problem of maintaining a productive classroom discourse becomes much harder to solve with counterintuitive ideas, such as the notion that a rather cold atmosphere could nevertheless have a heating effect on the earth's temperature (because even a cold atmosphere radiates back more heat than no atmosphere at all):

1. Researcher has the air to be hotter than the earth?
2. Josephine ehr..
3. Georgina well, in order to heat something, it usually must have a higher temperature […]
4. Harry heat or keep warm, that is a major difference.

In this case the students contribute little to identifying a plausible mechanism, but the teacher tries to keep them involved by providing 'hands-on' experience:

1. Teacher hold out your hand, hold out your hand, don't touch [holds his hand close to Josephine hand]. Some people say, do you feel the magnetic field
2. Josephine I feel your heat […]
3. Teacher whom of us is warmest? Normally spoken?
4. Josephine my hands are always very cold
5. Teacher ok… that should be a minor difference, shouldn't it?
6. Josephine but if I would be warmer, I wouldn't feel your heat. In that case I would believe [it] to be colder
7. Teacher no, because I emit
8. Josephine oh.
9. Teacher you do the same

Apparently, this demonstration does not suffice to close the gap between the students reasoning and the physics at hand. In the end, the teacher draws the desired conclusions himself. Most difficulties of this type were related to explaining equilibrium temperature as a ‘zero-sum dynamic process’ and, more specifically, to the detailed working mechanism of the greenhouse effect. In the other episodes, the agreed solution approaches were much more grounded in students’ ideas about how to proceed compared to the first design.

In order to allow students some room to make the models their own, we had planned that students would work on with their own estimates for quantities such as albedo. With the first version of the material we found that, when students had made their own estimates, teachers picked one correct value, rather than encouraging students to proceed with their own estimate.

1.	Teacher	which part of the earth is clouded? You need to know because clouds have a very high albedo
2.	Students	1/10? 20%? 30?
3.	Teacher	who says more?
4.	Student	70?
5.	Teacher	70%, who says less?
6.	Student	50%.
7.	Teacher	50%, let’s put it to that
[…]		
8.	Student	yes, but clouds could be above the ocean as well? In that case, it won’t be 2/3 water
9.	Teacher	ok, so your homework is 2/3/ ocean 1/3 land, half of the ocean is clouded [further details about input values] and then you compute, and take care that the outcome will be 0.30. Let’s agree on that, 0.30? You shouldn’t be too clever, should you?
10.	Student	Sir, one time we should be very accurate, and next time I try to be very accurate, and you don’t appreciate

As a result, students had little real say over their models. Although we tried to address this problem in the teacher preparation for the second round, it proved a rather persistent aspect of the classroom culture, which was maintained not only by the teachers, but also by the students who kept asking for correct answers.

DISCUSSION AND CONCLUSION

As a main outcome of this study we identify and validate some critical features of an authentic modelling experience, obstacles to achieve such an experience, and possible remedies. First, our findings confirm that, in order to engage in an insightful modelling process, students need to have solid prior knowledge, and sufficient expectations to guide their explorations. Therefore, we conclude that foundational physics and mathematics knowledge should be taught before rather than during the modelling experience. In order to make such knowledge available for modelling purposes, it might be advisable to teach types of model structures as templates, along the lines proposed by Fuchs (1997). Moreover, based on the same argument, really advanced, or novel applications, such as chaotic behaviour, might also better be taught in a separate follow up module, in a more guided fashion.
Moreover, students find it difficult to see how behaviour emerges from ‘instantaneous relations’ (e.g. differential equations). If the dynamic behaviour of systems is deemed important, which we think it should be, teaching should focus on describing the rules of change in terms of differential equations, even for rather simple systems that can be described by a closed-form expression (as an explicit function of time).

Finally, we touched upon the delicate balance between guidance and freedom. While some guidance is needed to provide a sense of direction, too much guidance may also hinder insightfulness. To take responsibility for the process, students must feel the need and have the opportunities to consider their own ideas seriously. Teachers were little inclined to let the students evaluate their own contributions, and the students were not used to it either. Thus, if students are to become independent modellers, the implications clearly go beyond a single series of modelling lessons, as the whole classroom culture will be affected.

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