A Qualitative Model of the Greenhouse Effect

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Abstract

Qualitative reasoning is traditionally associated with the domain of physics, but to promote widespread use of qualitative models, the domain of application should be expanded. This paper investigates the application of qualitative reasoning in the domain of the Greenhouse effect. This research is an effort in representing knowledge about processes and flows of energy in the radiation cycle, for educational purposes. It discusses requirements for model building in this domain, and the consequences that follow from the different nature of ecological domains.

1 Knowledge Communication Models

1.1 Introduction

Humans reason about the world with finite knowledge. They interact with systems without knowing every detail about that system, and they seem to be doing pretty well, not bothered by this 'incompleteness' in their daily routines.

When pouring a cup of tea (figure 1), we know that we need to put the spout above the cup, hold the teapot in a certain angle, and change the angle as the teapot contains less tea until the cup is full. If the cup is full, we hold the pot in a horizontal angle and the tea stops flowing. To pour a cup of tea we do not need to know the exact location of where to hold the pot, it is sufficient to know the spout is above the cup. We do not have to know the exact angle to hold the pot for tea to pour out; depending on the amount of tea that flows out of the pot, we know when to change the angle. Moreover, we do not need to know the exact amount of tea or the size of the cup to see whether it is full, we can tell by the level of tea in the cup. For dealing with most things in life, we do not have and do need not to have complete, detailed information about a system in order to interact with it.

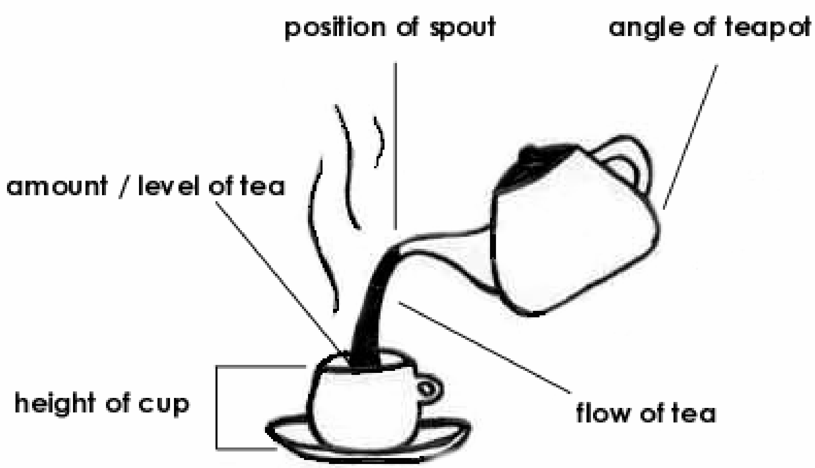

Figure 1: Pouring tea

For most situations, having an abstract *model* of a system is sufficient. For certain tasks, such an abstract model is even more appropriate then having detailed numerical information. However, the majority of simulation techniques need quantitative knowledge of a system to be able to make inferences about the behaviour of that system. These techniques usually require more *detail* than is available. Qualitative or model based reasoning aims to solve this *resolution problem* by creating techniques and implement computer programs that can reason with low resolution, partial information (Forbus, 1996a). Furthermore, qualitative reasoning is interested in understanding how one can draw useful conclusions about the properties and behaviour of systems with as little detail as possible (Forbus, 1984).

Moreover, if quantitative or detailed data *is* available, this information, when implemented, will often provide a single, precise, narrow answer to a single question. For many tasks though, such an answer is insufficient. In contrast, a qualitative simulation will generate all possible outcomes from an incomplete, qualitative description (model). Qualitative reasoning thus supports easy exploration of alternatives within a space of possibilities, while a numerical method requires precise values for variables even if they are unknown.

For a system to be able to teach, it needs to do more then just give exact answers to questions. It needs to be able to explain its reasoning. A calculator does its job well, providing precise answers for specific questions, but it would fail as a teaching device or system because it does not have the ability to explain the mathematics involved. An educational system should be able to communicate its reasoning and in order to do this it needs an explicit representation of the qualitative knowledge and reasoning involved in such tasks (Wenger, 1987). Such a system needs knowledge of how the answers relate to the questions.

Qualitative models are built to be able to reason about physical systems, with the goal of predicting and *explaining* the behaviour of those (simulated) systems. This requires explicit causal models of a system’s behaviour to relate that system's behaviour at time *t1* to some behaviour at *t2,* as well as a representation of its physical structure (Bredeweg & Winkels, 1998). The notion of *causality* is an essential element in human and qualitative reasoning for it provides justifications of the predicted behaviour (Forbus, 1984). The ability to facilitate knowledge communication due to this explicit representation of causality makes qualitative reasoning well suited for the construction of intelligent tutoring systems (ITS) or interactive learning environments (ILE), and has therefore become one of the central motivations for research activities in Artificial intelligence and education

(Forbus, et al, 2001). The common use of causal models for reasoning makes qualitative reasoning more similar to human reasoning then other techniques or methods.

For students to become good problem solvers, they need the opportunity to learn how to integrate and structure their knowledge instead of just memorising facts. Computer based learning can facilitate such active learning (Khuwaja, 1994). Despite the fact that a considerable part of a problem-solving task in physics can be done qualitatively, students often try to memorize formula without knowing how and when to apply them as they often lack a good view of the problem situation (Forbus, 1997). Qualitative reasoning can help students to get to know a system qualitatively, and get a good view of the problem context instead of immediately trying to figure out what to quantify. Alternatively, as De Kleer & Brown (1984) put it, "even when axiomatic theories are available, it is only after careful qualitative analyses that it becomes clear which equations apply to a certain situation." The reverse is also true, to make sense of the output of a numerical simulator, a person must still be able to interpret the numbers to identify important qualitative characteristics of the behaviour (Iwasaki, 1997). A great deal of research has shown that computer simulations can indeed support learning (Bredeweg & Winkels, 1998).

To be able to use qualitative models for educational purposes, a library of 'off-the-shelf' models should be available (Forbus, 1996b). At present, most of the models that have been constructed deal with systems from the domain of physics. Physics has a long history of theory building with a strong mathematical foundation. However, physics is not the only domain where qualitative models can be of use. To come to a widespread use of qualitative reasoning, a library should contain qualitative models from a variety of domains. The types of problems in ecology, as for instance resource management and sustainable development, can also benefit from the qualitative reasoning techniques by simulating the behaviour of ecological systems. Ecology is a domain where a lack of (quantitative) knowledge about certain phenomena creates a need to reason with the available qualitative knowledge (Kropp & Eisenack, 2001). Except for a few examples[1], little research is available on the construction and use of qualitative models for non-physics

[1] Several ecological and social science models are discussed in section 1.3

domains for educational purposes. For this reason, this thesis focuses on the construction of a qualitative model for the Greenhouse effect (chapter 2), where an emphasis lies on the educational aspects that are considered when constructing such a model.

1.2 Representing Qualitative Knowledge

The framework that specifies the way knowledge about a domain should be represented can be called *ontology*. Ontology represents a shared understanding that can function as a unifying framework for different viewpoints and serve as a basis for communication between people and systems (Uschold & Gruninger, 1996). J.F. Sowa (Sowa, 2003) gives a definition of ontology;

> "The subject of *ontology* is the study of the *categories* of things that exist or may exist in some domain. The product of such a study, called *an ontology*, is a catalogue of the types of things that are assumed to exist in a domain of interest **D** from the perspective of a person who uses a language **L** for the purpose of talking about **D**. The types in the ontology represent the *predicates*, *word senses*, or *concept* and *relation types* of the language **L** when used to discuss topics in the domain **D**. An un-interpreted logic, such as predicate calculus, conceptual graphs, or KIF, is *ontologically neutral*. It imposes no constraints on the subject matter or the way the subject may be characterized. By itself, logic says nothing about anything, but the combination of logic with an ontology provides a language that can express relationships about the entities in the domain of interest."

Constructing an ontology means committing to a certain worldview. Ontological commitments are essential to knowledge representation as they provide the opportunity to select issues from the complex, real world that are believed to be relevant for the task at hand (Davis et al, 1993). The more specialized an ontology is, the more difficult it is to reuse or share its knowledge. A large part of the modelling task consists of making assumptions about the world. Making these ontological assumptions explicit is essential for a shared understanding. As not all assumptions and modelling decisions are obvious to everyone, implicitness of these assumptions can lead to misunderstandings and disagreements. Making decisions explicit makes the knowledge base transparent and facilitates the communication of knowledge. Moreover, explicit assumptions enable better reusability of (parts of) an ontology for they determine the range of application (Uschold & Gruninger, 1996).

1.2.1 Techniques for Qualitative Reasoning

With the main goal in qualitative reasoning being communication of knowledge, a strong link exists with cognitive theories of human cognition and communication. Formalizations must be able to build on and link to the cognitive representations of whomever the model is build for to provide a semantic and intuitive meaning. Three main approaches to qualitative reasoning exist, each using different ontological commitments and worldviews.

The component-centred approach proposed by De Kleer and Brown (1985), uses the ontological commitment of seeing the world as a (very complex) machine. The authors do this by modelling the world consisting of components that manipulate materials, and pipes that transport materials. To facilitate reusability of models, behaviour is seperated from the structure of the device. The constraint-centred approach (Kuipers, 1986) has an emphasis that lies more on mathematics translated into a qualitative formalization, then on some theory or ontology of (human) qualitative reasoning. Kuipers' approach does not represent any entities nor supports construction of a library from which one can choose models. Forbus (1984), in his Qualitative Process Theory (QPT) does have a cognitive foundation. He tries to stay close to the way humans reason about the world. In his approach, the world is modelled as objects that have properties that can change over time (quantities) and these changes occur through processes. QPT defines a notion of physical processes that appears useful as a language in which to write dynamical theories. This is especially relevant to ecology, because it corresponds with the way people look at ecological systems, (Salles et al, 1996) which is not so much a machine-like view, but a view more focussed on entities and processes.

1.2.2 General Architecture for Reasoning about Physics, GARP

Bredeweg (1992) has proposed an integrated approach based on the unifying principles of the KADS methodology. The result is GARP[2], a domain independent

[2] http://web.swi.psy.uva.nl/projects/GARP/

qualitative simulation tool, implemented in SWI-Prolog that allows users to simulate the behaviour of systems.

In GARP, domain knowledge is represented in a library of model fragments that do not need to map directly to real world objects, but can be functional abstractions, and combines component and process views. GARP has representations of entities, their structural relations, time varying quantities, and dependencies between quantities and values of quantities. Behaviour is derived from a scenario with some initial values by comparing the behavioural features specified in the model fragments (Salles & Bredeweg, 1997).

1.3 Ecological and Social Science Models

As mentioned earlier, most efforts in qualitative reasoning have been concerned with the construction of models for physics and engineering problems. However, the field has spread to other domains as well, where new problems concerning the construction and application of qualitative models arise. Next, some of these models from the domain of ecology are discussed.

In ecology, there is a need for modelling and simulation tools for students, researchers, and decision makers. Experimenting with, for instance, different means of managing ecological systems is made possible by using simulations. Ecology deals with dynamic systems that can show very complex behaviour, even if they are relatively simple, which makes them hard to understand. For this reason, modelling is already widespread in the field of ecology. Most modelling and simulation techniques used in ecology though, are of a quantitative type, expressing the measurements taken from nature and the mathematics involved to make (local) predictions (Salles et al, 1996). Observing and measuring ecological processes is hard and these processes are therefore hard to quantify, so ecologists, somehow, have to deal with incomplete knowledge. Moreover, the knowledge regarding ecological phenomena and processes is often of a qualitative nature (Struss & Heller, 1997). This is one of the reasons for the growing interest in using qualitative reasoning techniques to support environmental decision-making. The fact that constructing a qualitative model forces the modeller to explicate the knowledge involved, is especially important in ecology, for it helps to develop to a deeper and broader understanding of causal implications of processes. Additionally, the need for communication in resource management and environmental decision-making makes a strong case for the use of qualitative reasoning (Struss & Heller, 1996).

Research about interactions among organisms or populations is of primary importance in theoretical ecology. Salles and Bredeweg (1997) constructed a qualitative model of the Brazilian Cerrado in GARP, to investigate the effects of fire (as a management tool) on vegetation communities. They created a library where the model fragments represent general knowledge about populations that can be reused in different situations. The goal of this research was to study the possibilities of qualitative modelling in an ecological domain. With their model, they investigated the influences of increasing or decreasing fire frequency on the openness or density of the vegetation and succession of population types. Based on this implementation of a qualitative theory of population dynamics, Salles et al. (2002) decided to use the library, containing the basic processes, to investigate the (primary) dynamics between two populations in more depth. The resulting model enabled them to derive complex community behaviour from first principles concerning interaction relations. The authors constructed a 'base simulation model' (p7) that describes the basic interactions between populations and models specifying the basic processes that describe the influences populations can have on each other. The types of interactions that exist between populations restrict their behaviour. For instance, the *predator-prey model* describes how a predator population changes with a prey population, the *competition by interference model* demonstrates the coexistence and competitive exclusion of one population and the *commensalism model* shows how one population increases when the other increases without influencing the latter.

Loiselle et al (2000) have used QR to identify secondary effects of management activities concerning the conservation of some species in an Argentine wetland. The aim of this research is to study the impacts of economic activities, population dynamics, transportation and energy production on the ecosystem. The authors use feedback mechanisms to investigate the impact of reduction in mortality of one dominant predator on the abundance of other key species in the ecosystem. Variables are calculated through a trophic web of sorts of species, some grouped and modelled as one variable, and effects are calculated through the web as being positive (chaotic) or negative (stable). Their modelling efforts resulted in some unforeseen negative feedback mechanisms between conservation efforts and abundance of certain species. The authors do not discuss their experience with qualitative reasoning explicitly. However, they do point out that, although it was good to be able to model and simulate their subject qualitatively, they missed getting quantitative results.

To investigate the socio-economic impacts of an over-developed fishing industry on marine resources, Kropp and Eisenack (2001) constructed a qualitative model applying the concept of qualitative differential equations (Kuipers, 1994). Ecological and political management suffer from a lack of methods for managing resources, and quantifying data due to the high level of complexity that comes from the combination of economical and biological interactions. Qualitative reasoning can prove a valuable guide to develop strategies and helps to arrive at a systematic view of causes and effects. The authors claim that their bio-economic model can facilitate a progress in scientific reasoning about environmental and economical systems (p6). In many cases, the solutions offered by the simulator were ambiguous. Concentrating on important variables made the outcomes easier to interpret, and usable to identify critical points for decision-making. However, Kropp and Eisenack state that the ability to change variables is not sufficient to make a qualitative model a good management tool. For adequate support, managers should be able to change structural aspects of models as well, to arrive at alternative solutions.

Kamps and Peli (1995) present a case study applying qualitative reasoning to a social sciences domain; the density dependence theory of organizational ecology. This theory describes the processes by which organizational populations grow and decline due to changing environmental conditions. Growth of an isolated population is a function of the population's density, and is affected by two opposing forces, legitimisation of a population and competition between the members of a population. The system is considered to be in an equilibrium state if the mortality rate and founding rate of organizations are equal, representing the carrying capacity of the resource environment.

Somewhat similar to Kamps and Peli, Brajnik & Lines (1998) constructed a model of socio-economic phenomena. This model describes an allocation problem for the quality of life, which is represented as a function of two variables, per capita consumption and an index of environmental quality (measured in amounts of greenhouse gases), plus some constraints. The objective is, as with the model of Kamps and Peli, to find an equilibrium state, which should represent the best way to assign unconsumed national income to obtain the best possible quality of life in a certain state of the system. The purpose of this model is to show what decisions can be made by the authorities that are beneficial considering a certain situation. For instance, reducing emissions in the production technology, or increasing capacity for producing consumer goods.

Kamps and Peli found that during the modelling process the original theory needed to be revised. Some scenarios had the simulator produce behaviour that was unaccounted for by the original theory and the simulator even generated some behaviour in contradiction to this theory. For this reason, extra constraints and assumptions were added to predict the correct behaviour. For example, one scenario allowed a population to grow exponentially into infinity, something that could never happen in the real world, as resources are finite. Brajnik & Lines (1998) stress the importance of theorists having to formalize their rules of thumbs when constructing a model. Finding implicit assumptions that need formalization for a model to show correct behaviour is one advantage that comes with the process of model building. Especially in domains where the available knowledge is ill-structured or un-formalized, the ability to generate behaviour from a model and test assumptions is useful.

Because of the complexity of these systems, the modelling task will help to gain a deeper understanding of the processes involved, and get a better view of the indirect impacts of influences. The models discussed above, with an exception of the models of Salles and Bredeweg (1997, 2002), are built to support scientific research and environmental decision-making. For this task, dealing with allocation problems and environmental management, a combination of qualitative and quantitative simulations appears useful to be able to use the results for decision-making.

1.4 Knowledge Models in Education

One of the central motivations for research in qualitative reasoning has been its potential for the construction of intelligent tutoring systems (ITS) and interactive learning environments (ILE) in general (Forbus, 1984). Interactive simulations can offer students the opportunity to learn about system behaviour, tuned to the specific needs of each individual user (Wenger, 1987).

The introduction of computer simulations as instructional devices has induced a renewed interest in the constructivist approach to education. This approach sees learners as active agents in the knowledge acquisition process instead of passive observers. Learning based on exploration with simulations relates to a specific form of constructivism, namely scientific discovery learning (Jong & Joolingen, 1998). Interactive simulations encourage students to become actively involved in the learning process. Tuned to their individual needs, students can explore and solve problems about complex, dynamical systems. Supporting students to have an active role in the learning process should help them to arriving at a better understanding of the behaviour of systems and scientific reasoning. This way students are encouraged to develop their own domain theories and learn when and how to apply scientific principles (Forbus et al., 2001). By building models and simulating them, learners can test these theories and see if they are accurate predictors of behaviour.

1.4.1 Organization of Knowledge

Whether people are successful problem-solvers depends for a great deal on the way they structure and organize their knowledge (Dunbar, 1993). Experienced problem solvers have organized bodies of knowledge. They use this organization to process and incorporate new knowledge and facts, and integrate these with existing knowledge. Novices, however, do not have such a structured organization and base their reasoning on superficial facts and knowledge. For this reason, they will not establish a deep understanding of the problem, as experts do (Lesgold, 1988).

Causality is an essential element in human reasoning. It allows the prediction of behaviour and provides justifications of the predicted behaviour (Iwasaki, 1997). Humans create causal models of the world and apply them to assess situations and learn to understand the world around them. The relation between cause and effect is not something that is directly observable though; experience teaches whether assumed relationships function properly as predictors of behaviour. Causality is a way to organise knowledge of the world, it is a ‘thinking tool’ and serves as a practical explanatory framework (Neri, 2000).

Many students have difficulty understanding the behaviour of ecosystems. Basca & Grotzer (2001), claim this is because students do not understand the underlying complexity of causality that comes with these systems and structures. Often, such systems behave in a counter-intuitive way. A misunderstanding of the levels of description, especially in systems where many interacting parts are involved can make it hard to solve problems correctly (Wilensky & Resnick, 1999). To use Wilensky and Resnick's example, students who simulated a traffic jam by implementing two simple rules for individual car-behaviour, could not understand why the traffic jam behaved differently then the cars did. While the cars were moving forward, the traffic jam was moving backward. One reason for their misunderstanding could be that the students tried to explain the behaviour of the traffic jam at the level of the individual interacting parts, which is a *micro level* view. However, a traffic jam is not a simple collection of cars, it 'emerges' from the sum of the *interactions* between the cars and does not follow the same rules of behaviour as the individual cars do. Wilensky calls the perspective of looking at the emerging behaviour of the traffic jam a *macro level* view. To get a deep understanding of the behaviour of dynamical systems it is important for students to learn the differences and relations between different views, for these views determine the causal representation that is appropriate for solving problems (Chi, 2003). White & Frederiksen (1990) support this view; they claim the difficulties arise from the complex of disjunctions among the multiple representations, models and epistemic practices that are used in teaching domain phenomena and scientific inquiry. If these levels and views stay unrelated and the right knowledge organisation is absent, it becomes impossible for someone to solve a problem *correctly*. An appropriate causal model is required to know which steps to take and in what order to solve a problem. Not having such a representation can be the reason why many students, when presented with a problem, immediately try to apply equations, instead of first getting a clear picture of the problem situation, as experts do (Koning & Bredeweg, 1998). Supporting students to structure and organise their knowledge will help them become better problem solvers.

1.4.2 Organization of Learning Material

Students can easily be overwhelmed by the freedom and complexity of learning with simulations; it can result in an unproductive mode of exploration (van Berkum & de Jong, 1991). Goals provide powerful constraints to the cognitive processes underlying scientific reasoning. The types of goals that are presented to a learner determine many of the reasoning errors that a learner can make (Dunbar, 1993). De Jong et. al. (1992) name several studies that have compared the effects of structured vs. unstructured environments that support discovery learning and found a strong advantage for a structured curriculum. This research implies that, whether students are engaged in exploratory learning or learning by building models, simulation-based learning can be improved with support from the simulation itself. Most of the time, the subject matter to be taught is too big to be presented to a student at once, it needs to be divided and organised in smaller parts. Salles & Bredeweg (2001) name three questions one needs to consider when planning a curriculum

- how to divide the subject matter
- with which unit to start the learning
- how to proceed through the learning material

This task of curriculum planning is not straightforward; some things, for instance, can only be learned when prior knowledge is adequate. Lesgold (1988) mentions some issues to which a curriculum, that supports multiple viewpoints on the material, should comply. A course must be *coherent*; each simple lesson should be relevant to all of the viewpoints one wants to teach. Each viewpoint should be *locally complete* and teachable from the models or lessons it contains. Viewpoints must be *globally complete* in the sense that they comply with the viewpoints experts use in that domain and are seen as important to teach. Finally, the lessons should be *relatively consistent*, in that the prerequisite relationships all run in the same direction. This means that no lesson should be a prerequisite for another when in some other viewpoint this relationship has an opposite direction.

In the qualitative reasoning community, learning is mostly seen as the construction and integration of mental representations, mental models. White & Frederiksen (1990) see learning as a process of mental model transformation, in which models become better organized, more coherent, more specific and contain fewer contradictions and misconceptions. Moreover, the authors consider problem solving as model manipulation. By focusing on the relationships between models, as for instance using a micro level model as a mechanism to explain basic operation principles of a macro level model, students should come to a better understanding of the disjunctions between models. The basic idea is that students have to learn about systems and their behaviour by acquiring appropriate (mental) models of physical systems and their behaviour. These models provide the basis for successful interaction with and problem solving about these systems (Salles &Bredeweg, 1997).

Within the scope of qualitative models for simulations, a well-known approach for structuring tutoring material is the model progression theory of White and Frederiksen (1990). Their approach deals with the mental model transformations and the complexity of simulations by proposing a progression of simulation models that resembles the way mental models evolve in students. Within the domain of electrical circuits, they propose a progression of qualitative, causal models progressing from naïve to expert levels.

The authors propose three **perspectives**; f*unctional models* describe the functional aspects of circuits, how subsystems and components interact to achieve the purpose for which they are designed. *Behavioural models* focus on the state changes of a device, and how these changes cause a change of state in some other device. *Reductionistic* or *physical models* show the behaviour of a device at a more micro level.

Order is a subdivision of the behavioural models. *A zero-order* model describes whether a component is on or off, or present or absent. A *first-order* model describes changes, and a *second-order* model describes *relative* changes in behaviour.

The **degree of elaboration** of a model is determined by the number of qualitative rules needed to determine the effects changes in states on other components.

According to White and Frederiksen, the progression of models along the dimensions of order and degree of elaboration should enable students to develop multiple models of, in their case, electric circuit behaviour. However, a 'deep' understanding of circuit behaviour can only be obtained when students can apply the other two perspectives as well. Their findings show how supporting students to construct derivational linkages among models enables them to understand the origins of circuit behaviour and applying laws to solve problems. The domain in which they constructed their theory, the electric circuit domain, can be seen as a well-structured domain that lends itself well to organise and construct models along these progressions. However, their claim is that this theory can be easily generalized to other domains.

Salles and Bredeweg (2001) propose a division of their Cerrado Succession model (Salles & Bredeweg, 1997) based on 'knowledge characteristics'. The authors claim that none of the proposed approaches such as the Genetic Graph of Goldstein (1979), Causal Model Progression of White and Frederiksen (1990), and the Didactic Goal Generator of Winkels and Breuker (1993), is sufficient for constructing progressive learning routes. Salles and Bredeweg (2001) propose a progression reusing specific parts of these approaches.

Generalization / specialization; this dimension organizes model fragments along a subtype hierarchy. Specialization of a model fragment results in a subtype of that fragment, whereas generalization points to a super-type, a higher concept in the hierarchy.
Analogy; within this approach, two model fragments are analogous when they are both direct subtypes of the same super-type.
Inverse; inverse is a special kind of analogy, which applies to activities or processes that have opposite influences.
Order; this dimension follows the causal model progression but with a different meaning for the zero-order notion. In an ecological domain, values cannot be simply 'on' or 'off', therefore the authors have relaxed this notion to the different values a quantity can have.
Structural change; structural change occurs when adding or removing entities from a model, i.e. changing the models structure.

Next, the authors discuss their model progression where 'progression' can happen *within* a cluster of models along the dimensions of generalization/specialization, analogy and inverse. Progression *between* clusters can occur along the order and structural change dimensions. Increasing the order represents a step from a static cluster to a cluster that describes behaviour. A cluster that describes a single population, can progress along the structural change dimension to a cluster classifying two interacting populations, and ends with a discussion of communities.

The authors have implemented this approach as a series of scenarios that can run simulations within each of these six clusters.

Research about the formation and use of mental models is a central topic for education in general, and for the design of tutoring systems in particular. White and Frederiksen (2003) have shown that creating coherence among multiple models through careful derivations of their linkages leads to higher levels of success in learning the models that represent a more scientific way of reasoning.

1.5 Concluding Remarks

Qualitative reasoning is a valuable technique for the construction of (intelligent) educational systems. The way qualitative reasoning can 'handle' incomplete knowledge seems to be closely related to the way humans reason. This makes this technique more intuitive then other simulation techniques, and appropriate for educational systems. Teaching students how to organize their knowledge and present them with multiple views on a system, can facilitate learning in a way that allows students to solve problems in a domain correctly. Science education can benefit from having tools that enable students to test their theories about certain system behaviour. In addition to the educational benefits, qualitative reasoning is a valuable technique for scientific research. In ecology, qualitative reasoning can facilitate the reasoning about systems despite the lack of precise quantitative knowledge as was discussed in section 1.3. To investigate the issues that are involved in constructing simulation models in an ecological domain, this thesis presents work in the construction of a qualitative model of an ecological domain, i.e., the Greenhouse effect.

2 The Greenhouse Effect

2.1 Introduction

The earth has a consistent mean temperature of 15^0C that is the result of the occurrence of gases in the atmosphere. Some of the energy that the earth receives from the sun is 'trapped' by these gases, and kept from leaving to space resulting in a warming of the earth. Because of this characteristic of these gases, they are called *greenhouse gases*. Without the entrapment of energy, the earth's mean temperature would be -18^0C and life, as we know it today, would not be possible. Since the beginning of the industrial revolution, human activities such as the burning of fossil fuels, deforestation and agriculture have caused the concentrations of greenhouse gases in the atmosphere to increase substantially. An observed rise of the global temperature has been related to these human activities and CO_2 emissions, and this temperature rise is believed to be the result of an enhancement of the natural Greenhouse effect. This awareness has lead many researchers to investigate possible causes and effects of this temperature rise. However, as much knowledge about the climate system is lacking, this research has lead to a great deal of debate. At the present, the way the climate system will respond to these human activities is hard to predict, for too many processes are not understood well enough. One undisputed reality though, is the fact that the global climate system *will* respond to increasing temperatures. Moreover, this response could have irreversible consequences for the habitability of this planet, and influence many lives and ecosystems. For this reason, many organisations, such as the United Nations, are currently debating about actions to decrease carbon dioxide presence in the atmosphere.

The first section of this chapter explains the natural Greenhouse effect that keeps the earth at a constant, comfortable temperature. The last section of this chapter discusses which processes are pointed out as causes of the increase in atmospheric gases, and describes some scenarios to illustrate ways the climate system may respond to restore its energy balance.

2.2 The Natural Greenhouse Effect

The sun radiates energy at a very short wavelength (figure 2) (1). When this solar radiation enters the atmosphere of the earth a couple of things happen; some of the short-wave energy is reflected by clouds (2) back into space, a small portion is absorbed by the atmosphere (3), and half of the short-wave energy passes freely through the atmosphere to reach the surface of the earth (4).

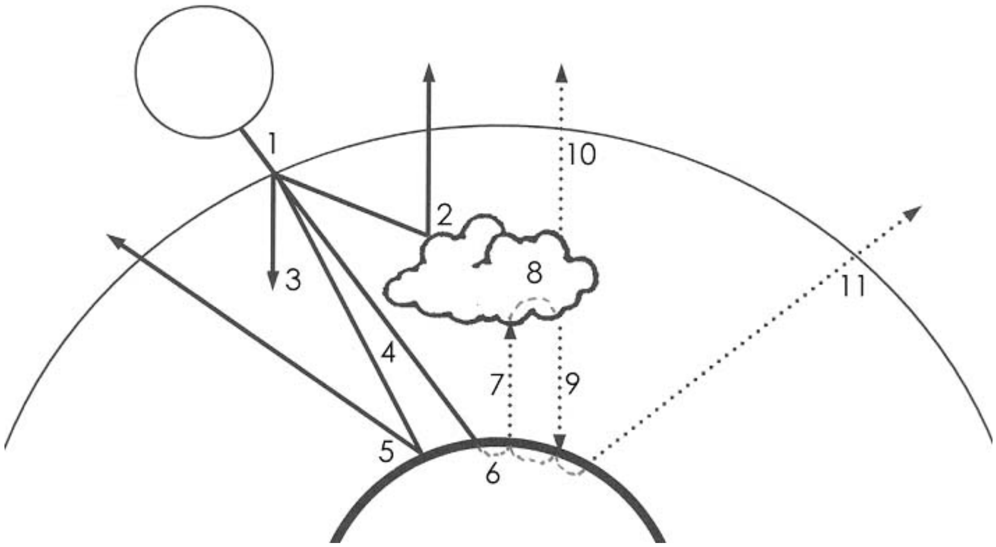

Figure 2: The Natural Greenhouse Effect

Of all the short-wave energy that has reached the earth's surface, a part is reflected by the surface (5) and part is absorbed by the earth's surface (6), resulting in a warming of the earth. The earth, being much cooler then the sun, radiates energy at a long wavelength (7). Greenhouse gases absorb this radiated long-wave energy (8). When greenhouse gases absorb the long-wave energy, they re-emit this energy again (as long-wave energy) both in the direction of the earth (9) and to space (10). As greenhouse gases do not absorb all long-wave energy, some is lost to space, resulting in heat loss (11). The earth again absorbs the radiation of long-wave energy by greenhouse gases, which also results in a warming of the earth. As a result of the presence of greenhouse gases the earth has two heat sources, one being the sun, giving direct energy by radiating light energy to the surface of the earth, the other being the re-emitted long wave energy by the greenhouse gases.

2.2.1 Radiation Laws

Radiation is the energy emitted as electromagnetic waves from the surfaces of all objects or bodies possessing a temperature above absolute zero. These waves can move through empty space but also through transparent materials (even solids). The type and amount of radiation emitted by a surface depends on the nature of the surface and its temperature. Heat is energy in the process of being transferred from one object to another along a temperature gradient. Wherever there is a temperature difference between two objects, heat energy will flow from the warmer object to the cooler object. Hence, radiation is a mechanism for energy transfer. The rate of emission of radiation is dependent on the emitting object's temperature[3]; the higher the temperature the more radiation is emitted. Moreover, radiation of an object has a certain wavelength that depends on the temperature of the object[4]. Objects with high temperatures such as the sun, emit short-wave energy and objects with (relatively) low temperatures, such as the earth, emit long-wave energy. If emitted radiation reaches another object a couple of things can happen; the energy can pass through the object, is reflected or is absorbed by the object. The absorbed energy can then be re-emitted (Strachan, 2002).

Absorptivity of a surface is the fraction of radiant energy that is absorbed by that surface. The portion of radiant energy that is reflected by a surface is called *reflectivity*, and the ratio of transmitted radiation of a surface is entitled *transmissivity*. Radiation that reaches a surface can be transmitted, absorbed or reflected, and these processes together account for the total amount of energy incident on a surface. A *blackbody* is a hypothetical object that absorbs the total amount of radiant energy incident on it; thus, no energy is reflected or transmitted. In addition, a blackbody re-radiates all of this energy, not dependent upon the type of radiation that is incident upon it. Materials that act as perfect blackbodies, as for instance soot, absorb all energy completely while the material gets warm. Other materials, as for instance glass, absorb very little light; the energy passes through the material. Materials that have a shiny surface, such as metal, do not absorb light either; the surface reflects incoming light. At normal temperatures on earth, most natural surfaces, as for instance water, soil and vegetation behave similar to blackbodies (Atkins, 2003).

The earth's surface, being an almost perfect blackbody (for long wave radiation), absorbs and emits much of the radiation incident on it to lower its temperature. Because of this balance between absorption and emission, the earth is said to have a thermal equilibrium. However, without the heat-trapping properties of the atmosphere this equilibrium temperature would be -18^{0}C. Because the atmosphere

[3] Stefan-Boltzmann's law
[4] Wein's displacement law

absorbs and emits radiation in a different way as a blackbody does, it is called a *selective* absorber. Objects of this type obey *Kirchoff's Law* that states that good absorbers at a particular wavelength are also good emitters at the same wavelength and poor absorbers at a particular wavelength are poor emitters at that wavelength. The greenhouse gases in the atmosphere are selective absorbers that allow the incident radiation from the sun to pass but absorb huge amounts of the radiation that the earth produces. This results in a heating of the atmosphere. The rates of absorption and reflection in the atmosphere and the surface of the earth determine the earth's *energy balance* (Atkins, 2003).

The fraction of incident radiation that is reflected by a planet or surface is called *albedo,* and concerns short-wave energy. Albedo values range from 0% for an object that absorbs all radiation to 100% for an object that reflects all radiation. The earth, being an almost perfect blackbody, has an average albedo of 30%. This reflective property has a cooling effect. The atmosphere has reflective properties as well, influenced by the amount and composition clouds. The global average albedo is, together with solar radiation, a major factor for determining the earth's short-wave energy input (Tynan, 2001).

2.2.2 Greenhouse Gases

Greenhouse gases are transparent for short-wave energy, absorb, and emit long-wave energy resulting in a warming of our planet. Alteration of the natural concentrations of atmospheric gases can have serious consequences for the temperature on earth. Common greenhouse gases are methane, nitrous oxide, ozone, water vapour and carbon dioxide, of which the latter two are the most influential. The next section describes the natural processes relevant to the exchange of carbon dioxide and water vapour between the earth and the atmosphere.

- Carbon Dioxide

Carbon Dioxide (CO_2) is the form carbon has when residing in the atmosphere. Carbon is the building block of all-live on earth, is stored in sinks, and exchanged between sinks and sources through processes. CO_2 accounts for 20% of the Greenhouse effect.

On land, the major exchange of carbon with the atmosphere is through photosynthesis and respiration in vegetation. Plants absorb CO_2 and light, and together with water and nutrients from the soil, use these materials for photosynthesis. Where photosynthesis is the process of making fuel for maintenance and growth, respiration is the burning of that fuel. Through respiration plants, animals and microorganisms in the soil release water and CO_2. Respiration does not equal photosynthesis; the difference goes into plant growth and plant material. Vegetation thus functions as both a *sink* and a *source* for atmospheric CO_2, depending on the balance between respiration and photosynthesis. Fire also plays an important role in the transfer of CO_2 from the land to the atmosphere. Fire results in a release of CO_2 from biomass and organic matter to the atmosphere. Carbon stored in sinks on land can be stored there for a very long time.

Oceans exchange CO_2 with the atmosphere mainly through the process of diffusion. The amount of CO_2 that oceans can hold depends on ocean temperature and the amount of CO_2 already in the ocean. Low ocean temperatures lead to a larger CO_2 holding capacity resulting in the uptake of CO_2. High ocean temperatures decrease the CO_2 holding capacity resulting in a release of CO_2 to the atmosphere. Organisms in the ocean consume and release huge quantities of CO_2 through photosynthesis and respiration. Dead plant and marine animal material sinking to the bottom of the ocean form the biggest carbon sink. These deposits are physically and chemically altered into sedimentary rocks, stored deep in the earth, and include for instance fossil fuel (coal, oil, and natural gases) (IPPC, 2001). Besides volcanic eruptions, CO_2 release from the sedimentary sink is mainly due to human actions and is discussed in section 2.2.

- Water Vapour

Water has two important properties that influence the earth's radiation budget. Water vapour is one of the most important greenhouse gases (water vapour makes up for 60% of the Greenhouse effect). In addition, clouds (water droplets and ice crystals) are reflective, and increase the albedo of the atmosphere, resulting in reflection of incoming solar radiation.

Atmospheric water vapour presence increases substantially with rising temperatures due to evaporation. This produces a positive feedback as increasing amounts of greenhouse gases further add to the global temperature. However, this feedback is counteracted by the increased reflection by clouds. Most theories claim that the combination of both reflection and heat trapping leads to a net cooling effect. Through condensation and evaporation, water vapour is added or subtracted from the atmosphere. These processes account for most of the energy transfer between the atmosphere and land, and are called latent heat fluxes. These fluxes do not directly influence temperature but are very important in driving the water cycle (Strachan, 2002).

2.3 Enhanced Greenhouse Effect?

A change in the composition of the atmosphere thus affects the earth's radiation balance between incoming short wave and outgoing long-wave radiation (radiative forcing). The earth responds to this forcing by trying to restore its balance by means of releasing warmth to the atmosphere (Wigley, 1999). Any factor that alters the amount of radiation received from the sun or heat lost to space may influence the climate. Therefore, any enhancement of the Greenhouse effect is a cause for concern. Besides fluctuations of solar radiation due to the earth orbiting around the sun, human activities influence the amount of greenhouse gases. In fact, since the beginning of the industrial revolution, carbon dioxide levels have increased with 35% (IPPC, 2001).

Two groups of influences on the Greenhouse effect can be identified; natural and anthropogenic. Natural processes were discussed above, such as, ocean-atmosphere exchange through diffusion, respiration and photosynthesis by plants and animals and volcanic eruptions. Anthropogenic forces are discussed in this section, as these are the human activities that disturb the natural carbon cycle, and possibly account for a global climate change. As discussed earlier, not only changes in amounts of greenhouse gases can result in changing the global climate, changes in the global albedo play an important role as well, as is described below as well.

The contributions of human activities to the amount of greenhouse gases in the atmosphere are well measured. The largest anthropogenic source of atmospheric CO_2 is the burning of fossil fuels by industry and transport. Fossil fuels are formed during a slow transformation process working on sedimentary rocks, the biggest natural carbon sink. This burning of fossil fuels extracts CO_2 from the fossil fuel deposit in a fraction of the time that it took the sink to accumulate it. This positive forcing results in warming by increasing the Greenhouse effect.

The second important human influence is land use changes, clearing land for logging and agriculture. Carbon dioxide is released from the vegetation sink as it decays or is burned, and after which the cleared land is used for other purposes. Because growing forests absorb large amounts of CO_2, cutting down or burning them not only leads to increases of CO_2 in the atmosphere, it also means the sink gets smaller, decreasing the uptake of CO_2 from the atmosphere. (Hansen, J. et al., 1998).

Relations between positive and negative forcings in the global climate system puzzle many scientists. *Negative feedback* factors have a stabilizing effect, reducing the enhancement of the Greenhouse effect, and *positive feedback* enhances the Greenhouse effect driving the earth system towards higher temperatures.

A few examples:

- increasing amounts of CO_2 in atmosphere → positively influences vegetation growth → increases absorption of CO_2 → slows CO_2 increase (negative feedback)
- increasing temperature → increases evaporation → increases water vapour in atmosphere → increases albedo → cooling (negative feedback)
- increased temperature → increases evaporation → increases water vapour in atmosphere → increases Greenhouse effect → warming (positive feedback)
- increased temperature → melting of icecaps → lowers albedo → warming (positive feedback)

As pointed out before, the increase of evaporation is believed to have a net-cooling effect due to increasing reflection of solar radiation. Other effects of increasing temperatures are the melting of icecaps and rise of sea levels that have far-reaching consequences for the habitability of this planet. Several issues need to be resolved to be able to predict how all these cycles function together as a whole, and how increasing atmospheric CO_2 influences the climate.

2.3.1 Scenarios

Predictions about future states of the earth's climate system predominantly focus on the impacts of human activities and are typically based on assumptions about future CO_2 emissions. These assumptions are used to construct scenarios for simulations to predict the way the climate system could respond to certain disturbances if these assumptions hold. Scenarios can describe single influences or combinations of influences, testing assumptions about the relative contributions of processes to global behaviour. Different organisations hold different assumptions about the relative contributions of disturbances. For instance, many mention land use changes as an important factor, but this is not included in IPCC scenarios because according to them it has only a small contribution to climatic forcing (Hansen).

As the impact of human activities is the most urgent issue in climate change debate, some scenarios are described based on different assumptions as to how the human socio-economic system could evolve in the future.

- Utopian scenario

Starting point in this scenario is a global policy that forces all countries to use sustainable energy. Industry and households solely use solar and wind as energy sources, and no CO_2 or aerosols are emitted by the industry. Moreover, no forests are cut or burned down, and even new ones are planted. This will make the forests function as a sink, absorbing CO_2 from the atmosphere. In this scenario, CO_2 in the atmosphere will decrease, assuming the global temperature will decrease.

- Doom scenario

The global community increases their CO_2 emissions, cut, and burn more forests. The cutting down of forests will have vegetation behave as a source of atmospheric CO_2, adding to the emissions coming from the industry. Increasing the GHG emissions, more long-wave energy will be recycled in the atmosphere, and this scenario will result in warming.

- Volcanic eruption

Besides human influences, a scenario describing a natural disturbance, a volcanic eruption, can show the behaviour of the climate system, as it restores its balance after this temporary disruption. Releasing much CO_2 and aerosols to the atmosphere, volcanic eruptions have a net cooling effect that lasts for a year, and after which the system will have restored its original balance.

For educational purposes, some hypothetical situations could prove usefull as well, to explain some of the concepts and processes. For instance, some exaggerated worldviews can be used, as for instance a glacier world, where the complete earth surface is covered with ice, increasing the albedo (hypothetically) to a maximum. If the albedo increases to its maximum, a simulation should show that the global temperature goes down, and no long-wave energy is produced. In the section describing the behaviour of the qualitative model of the Greenhouse effect, some of these are discussed.

2.4 Discussion

Discussions about the enhanced Greenhouse effect concern many complex issues relating to the relationships between the numerous simultaneous processes. In climate research, very specific, highly detailed, mathematical simulation models already play a big role, and qualitative simulation can add to that research by testing potential theories and scenarios.

There are many uncertainties in the knowledge about the climate system and this makes it difficult to develop policies that introduce appropriate measures to decrease human influences. One example of an unforeseen element was the role of aerosols that in recent years became clear and is becoming an important factor in climate discussions. Where greenhouse gases have a warming effect, clouds and aerosols have a cooling effect and put together these forcings form a balance. Some regulations to have the industry produce 'cleaner' emissions were implemented, decreasing the aerosol contribution. However, this so-called 'cleaner' production lead to a stronger greenhouse forcing with the decreasing of aerosols, as these counteract the warming of greenhouse gases. Many contradictions exist, and the model discussed in the next chapter, tries to stay away from these debates as much as possible. Instead, the goal of this model is to make assumptions explicit. However, it is beyond the scope of this paper to suggest that the model will contribute to the scientific discussion about the Greenhouse effect. The modelling effort is an exploratory effort in the construction of a qualitative model in this domain. Scenarios, as described above are used to simulate behaviour of the climate system for educational purposes, explaining effects and consequences of the human factor.

3 A Qualitative Model of the Greenhouse Effect

3.1 Introduction

This chapter describes a qualitative model of the Greenhouse effect. The discussion of the Greenhouse effect (GHE) from the previous chapter is used as knowledge base for the construction of the model that is build to reason about the behaviour of the atmosphere-earth system within the radiation domain.

The first section of this chapter discusses the conceptual model. Here the relationships between the main concepts and learning goals of the Greenhouse effect are presented. Section 3.2 discusses the implementation of the model in the model-building tool Homer[5]. Section 3.3 discusses the simulation of the model, and the behaviour of the system. Section 3.4 concludes this chapter with a discussion.

3.2 Conceptual Model

A large part of the model-building task consists of the construction of a conceptual model. A conceptual model contains the main knowledge concepts and relations between concepts that represent the behaviour of the system. A conceptual model consists of two types of building blocks, concepts that make up the *structure* of the system and concepts that represent the *behaviour* of the system.

Learning goals are needed to ensure that the relevant concepts for teaching the Greenhouse domain are included. In most course modules,[6] the learning objectives of the Greenhouse effect are focussed on the relationship between radiative balance and the earth's surface temperature. To understand the GHE, and the radiation cycle, an understanding of the following concepts is required;

- *Atmospheric albedo*: The presence of water in the atmosphere will cause some the incoming solar radiation to be reflected into space.
- *Earth surface albedo*: The surface of the earth is composed by different substances that determine the earth's albedo. This albedo determines the absorption of incoming sunlight, and thus influences the radiative balance of the earth.

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[5] Homer can be downloaded from http://web.swi.psy.uva.nl/projects/GARP/software.html
[6] See for one example the NASA website http://icp.giss.nasa.gov/

- *Greenhouse gases*: As Greenhouse gases absorb long wave energy radiated by the earth and radiate this energy back to the earth, their presence can be understood as being a second heat source next to the sun.
- *Radiative balance:* An object that has equal rates for absorption and radiation is called to be in *thermal equilibrium.* Theories about the Greenhouse effect claim that the increase of greenhouse gases in the atmosphere causes the earth to reach a new equilibrium state at a higher temperature because of a disturbance of the earth's radiative balance.

The most important learning goal is understanding the fact that the earth needs two heat sources (i.e. the sun and greenhouse gases) to maintain a temperature at a normal level. Changes in the impact of the heat sources will have consequences for the temperature at the earth's surface.

- **Radiation**

A common way to represent the exchange of energy between entities is by means of *flows* that are triggered by an inequality. A number of qualitative models work by this principle, for example the U-tube model (Forbus, 1984). In this model, a flow of liquid is started from one container to another by an inequality between amounts of liquid in the containers. The initial plan was to model radiation as a sort of heat flow, where differences in temperature cause energy to be exchanged between objects. However, radiation works different from a heat flow. There are three ways heat can be transferred from one object to another. *Conduction* is the transportation of heat through solid materials, *convection* is the transportation of heat through fluids, and *radiation* is the transportation of heat through empty space. Where the first two mechanisms for heat transfer are started by an inequality in temperature between objects, radiation does not depend on this fact. As explained in the previous chapter, an object, with a temperature above absolute zero, radiates independent of temperatures of nearby objects. The balance between absorption and radiation processes, determines equilibrium situations, which will be demonstrated further on in this chapter.

- Basic processes for energy

If energy, that is **radiated** from one object, reaches another object (figure 3), this energy becomes 'incident' on the surface of the receiving object, which means the energy is located *on top* of an object (i.e. incident energy). Three processes operate on this energy:

1) Incident energy can be **absorbed**. The energy from the surface is transported to the inside of the object, after which it becomes *stored energy*.

2) Incident energy can be **reflected.** The energy is transported from the surface of object A to the surface of object B.

3) The third processes that influences incident energy is **transmission** that transports the incident energy *through* the object it was incident on, to another object's surface.

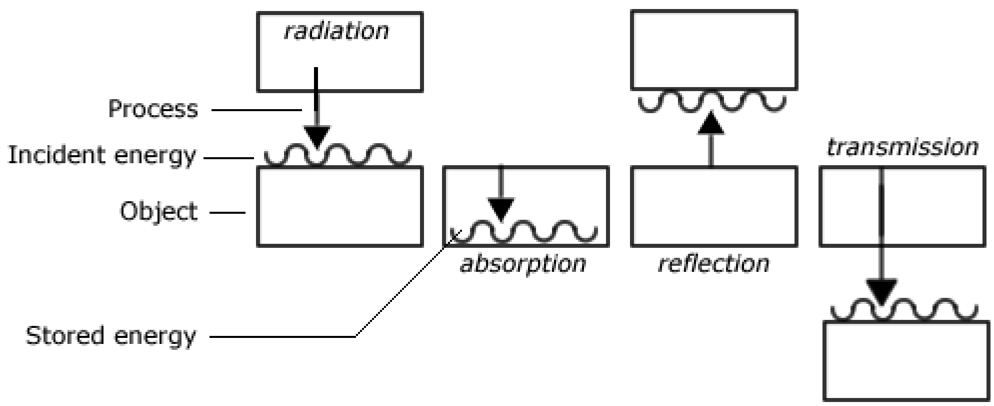

Figure 3: Basic processes for energy

Not all of these processes apply to all types of energy and objects. In addition, some modelling decisions were made to exclude some of the processes from the Greenhouse domain (see figure 2). As explained in the previous chapter, incoming sunlight is, if it is not reflected by clouds or transmitted by the atmosphere, for a small part absorbed in the atmosphere. The atmosphere being a selective absorber radiates this absorbed short wave energy, *as* short wave energy. For this reason absorption and radiation of short wave energy do not add extra behaviour to the earth-atmosphere system, it only represents a time-laps in the release of this energy. In addition, as the incoming sunlight is a continuous flow, as well as the absorption and radiation processes are continuous, and there is little variation in the amounts and rates of the processes, the modelling decision is made to exclude these processes from the model. This decision makes the absorption of short wave energy exclusive for the earth. With the short wave radiation excluded from the model, the only type of energy that can be radiated is long wave energy. Another process that is excluded is the reflection of short wave energy at the underside of clouds. Only a small part of the energy reflected by the earth is being reflected again by clouds back to the earth. For the same reasons as noted above, this process is excluded from the model, for it represents a particularly small flow, and does not add any extra behaviour to global behaviour of the system, as this energy is eventually reflected into space by the earth, or is absorbed by the earth. Transmission only occurs in the atmosphere and applies to both types of energy.

3.2.1 Building Blocks

The first step in determining the main building blocks of the conceptual model is finding the main relevant **entities** that make up the structure of the domain. Entities are defined by their permanent properties. Figure 4 shows the main entities:

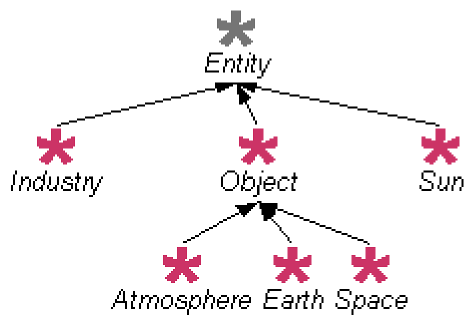

Figure 4: Atmosphere, earth and space are seen as objects for they share many properties that can be represented at an object level. The sun and industry are treated as separate concepts.

Modelling decisions

Initially the surfaces of the objects were represented as entities in the conceptual model, connected to objects. As surfaces play an important role in the radiation story it seemed logical to represent them separately from the objects they belong to, in order to construct views that deal only with the processes at the surfaces. As most of the processes in the radiation cycle deal with quantities belonging to surfaces, the role of the object itself, besides being a storage container for energy, became unclear. In addition, because of the exclusion of the processes mentioned earlier, a distinction between the top and bottom layer of the atmosphere was no longer needed. The introduction of surfaces as separate entities was needed to be able to make distinctions between processes at both layers of the atmosphere, as for instance reflection, which can happen simultaneously at two places in the atmosphere. It was decided that the object and its surface could be seen as a whole, where the surface is represented indirectly by the *incident* quantities (discussed below). This decision simplified the model by excluding the energy exchanging processes between an objects surface and the 'inside' of the object.

The decision to model objects without explicit surfaces can be illustrated by the difficulties that arise when giving the atmosphere two surfaces. Indeed, the atmosphere does not really have any surface that is either reflective or absorptive. The presence water vapour accounts for the reflection of short wave energy, and greenhouse gases account for the absorption and storage of energy. A decision to model surfaces as distinct entities would mean that, in the absence of water vapour, the atmosphere would not have a top surface. To make things a bit more complicated, the amount of water vapour would determine the *size* of the surface. Moreover, the incident LW energy is actually not incident on the bottom of the atmosphere but on the gas molecules that are greenhouse gases. The concept *incident energy* in this model, does not explicitly enforce the presence of a surface. Energy, if it is incident on an object could actually also be incident on something unspecified inside of the object. In this model, this option is left open.

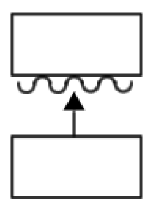

Figure 5: Placing of objects

Another modelling decision was too leave the placing objects implicit (figure 6). The objects exchange information through paths, but are not explicitly connected. This means that radiation of energy can travel through space before reaching another object, or arrive at another object immediately.

Other conceptualizations then the one chosen for this model can be thought of, such as the explicit representation of gases and water vapour as entities with amounts contained by the atmosphere. However, in this model the focus is on the flows of energy between objects in a general way, and not on detailed processes occurring within and between substances. Of course, if one wishes to discuss these details, the facilitation of this model to provide a more detailed view, should be investigated.

Structural relations represent the way the different entities are connected to each other. These connections are needed to have the entities be able to influence each other through processes. The structural relations between the objects in this model are represented by paths that enable the exchange of energy (figure 6).

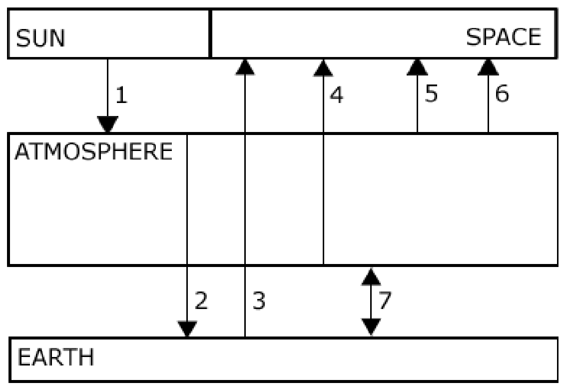

Figure 6: Structural relations

1: The sun is connected to the atmosphere with a *radiation path*. This enables the flow of short wave radiation from the sun to the atmosphere.
2: The atmosphere transmits the solar radiation to the earth through an *SW transmission path*.
3: Short wave energy that is reflected by the earth is transported to space by a *reflection path*.
4: Radiated long wave energy that is not absorbed by the atmosphere is transported by the atmosphere to space by an *LW transmission path* (represents heat loss).
5: Short wave energy that is reflected by the atmosphere is transported to space by a *reflection path*.
6: Radiation from the atmosphere is transported to space by a *radiation path* (represents heat loss).
7: The radiation exchange between the atmosphere and the earth is captured in a *radiation path*.

In GARP, behaviour is represented by **quantities***.* Each entity has certain properties that can change during time under the influence of processes. This change is represented by the change in value from a predetermined set of ordered values belonging to the quantity, i.e. **the quantity space** (figure 7). The values in a quantity space represent distinctively different states an object can have for that particular quantity. For example, in figure 1, the cup has the quantity 'level of tea'. This quantity, for instance, could have a quantity space of {empty, half-full, full}. These are all the possible, ordered values this quantity can have, each representing a unique, different situation. When certain processes (represented by *rates*) influence the quantity 'level of tea', when for instance pouring tea in the cup, behaviour is represented by the fact that the quantity value changes from an initial value {empty} to a value {half-full}. Changes in the value of a quantity space are shown by the *derivative* (∂) of the quantity (figure 5) that can have the values: plus, steady, min, representing the direction of change of a value in the quantity space. Note that while the number and type of values in a quantity space can vary, the derivative can only have the three values noted above.

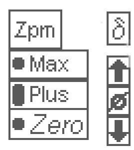

Figure 7: Quantity space {zero,plus,max}
with derivative values {plus,steady,min}

Values in a quantity space can be of the type *point,* or *interval.* A point value (values {max} and {zero} in figure 7) represents single value, that will be abandoned (if there are neighbouring values) when it increases or decreases. An interval value ({plus} in figure 5)represents a range of values that are not explicitly represented; therefore, an interval value can increase for an undetermined amount of time without having to change its value, to another value in the quantity space. Quantity spaces of different quantities are unrelated, this means that if, for instance, two quantity spaces belonging to different quantities both have the values max (figure 8), it does not mean these values are equal.

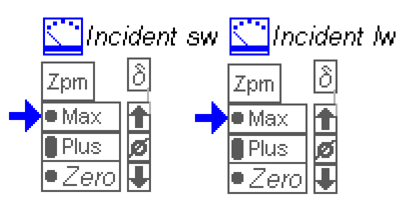

Figure 8: Two quantities with the same quantity space.

Blue arrows indicate that both quantities have the value max.

If these one wants to state that they are equal this needs to be made explicit by a adding a relation between these values. The value zero is an exception; this value is equal for all quantities.

As simulation is all about behaviour, choosing quantities and quantity spaces is one of the most important parts of the model-building task. Quantity spaces should facilitate the generation of all the possible distinct qualitative states that are important for showing the desired behaviour of the system. Quantity spaces should facilitate the generation of all the possible distinct qualitative states that are important for showing the desired behaviour of the system. Quantity spaces that facilitate too much variation will lead to the generation of many states that show little distinction. Therefore, one rule for defining quantity values is to determine the *minimal required variation* (bert & paulo). The relationships between quantities and the processes that influence quantities represent the *causal structure* of the model.

3.2.2 Entities, Quantities, Values and Dependencies in the Greenhouse Domain

In this section the entities, their quantities and dependencies are discussed, as well as a global description of the processes. This section will be concluded with a causal representation of the Greenhouse effect, combining the entities and their dependencies.

Object View

At the object level, the quantities are defined that apply to all sub-classes of object, i.e. atmosphere, earth and space (table 1). The surface of an object is implicitly represented by the quantities *incident long wave energy* and *incident short wave energy*. These quantities are needed to represent energy arriving at an object after it has been radiated by another object. Objects cannot directly interact with each other’s energies, and this intermediate quantity is needed to have the different processes be able to influence the energy arriving at an objects surface and divide this amount to the different flows of the radiation cycle. All of the quantities have the quantity space {zero,plus,max}, which represents that there is nothing, something or a maximum. These quantity spaces may not actually be the best conceptual representation of the states a quantity can have, the reason for the decision is discussed in the implementation section.

Table 1: Object quantities

Quantity	Quantity space	Quantity	Quantity space
Incident LW	{zero,plus,max}	Stored energy	{zero,plus,max}
Incident SW	{zero,plus,max}	Temperature	{zero,plus,max}
LW absorption	{zero,plus,max}	Radiation	{zero,plus,max}
Albedo	{zero,plus,max}	Reflection	{zero,plus,max}

Every object has an amount of *stored energy* (figure 9). As more energy is stored in an object, the *temperature* rises. In addition, as explained earlier, all objects that have a temperature above zero have *radiation* rates proportional to their temperatures. This is represented by the P+ relation, which means that there is a positive *proportionality* relation. This describes the causal relation that, for instance, a change in temperature causes a change in the radiation rate proportionally. Furthermore, an object has an *albedo* that represents a certain property of an objects surface. The albedo determines the reflection rate of short wave energy, where the reflection processes causes the incident SW to decrease (and increase at some other object's surface).

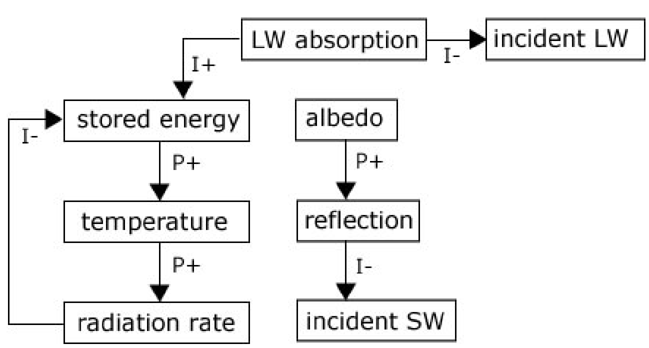

Figure 9: Object view

Stored energy is positively influenced (I+) by the *absorption* rate. At this object level, long wave absorption can absorb incident LW energy while increasing the amount of stored energy. The absorption process can best be understood as an internal process of an object. It transports the long wave energy from the surface of the object to the storage ‘container’. Processes influence quantities though proportionalities (P+/P-), or influences (I+/I-). The absorption rate influences the stored energy through a *positive influence* (I+), which means that if the process is running (has a value above zero) it causes the amount of stored energy to increase (as illustrated in figure 10).

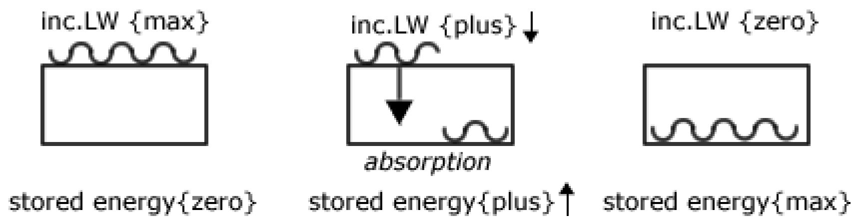

Figure 10: Absorption of long wave energy

This energy is taken from the surface of the object, thus the absorption processes, while increasing the amount of stored energy, will decrease the incident long wave energy at the surface of the object (I-). As more energy is stored in the object, the temperature of the object rises, and so will the radiation rate. However, at the same time, the radiation process releases energy from the object and causes the amount of stored energy to decrease (I-).

Remarks:

In the radiation domain has proved difficult to distinguish characteristic landmarks to determine the values of the quantity spaces. All processes are continuous, apply in every situation and only differ in relation to each other where they have a slightly larger or smaller influence. For instance, there will always be an amount of water vapour in the atmosphere, and there will never be that much as to close of the atmosphere to reflect all incoming solar radiation. However, to explain the effects of this gas the quantity space has been given the values {zero,plus,max} to represent exaggerated situations.

Atmosphere View

Besides the quantities that the atmosphere inherits for being a subtype of object, it has some exclusive quantities and dependencies (table 2).

Table 2: Atmosphere quantities

Quantity	Quantity space	Quantity	Quantity space
SW transmission	{zero,plus,max}	LW transmission	{zero,plus,max}
H2O	{zero,plus,max}	GHG	{zero,plus,max}
CO2	{zero,plus,max}		

In the atmosphere, incident SW energy is either reflected or transmitted, depending on the albedo (figure 11). Increasing albedo values, lead to increasing reflection and decreasing SW transmission rates, and a maximum value for albedo means that all the incident SW energy is being reflected, and none is transmitted.

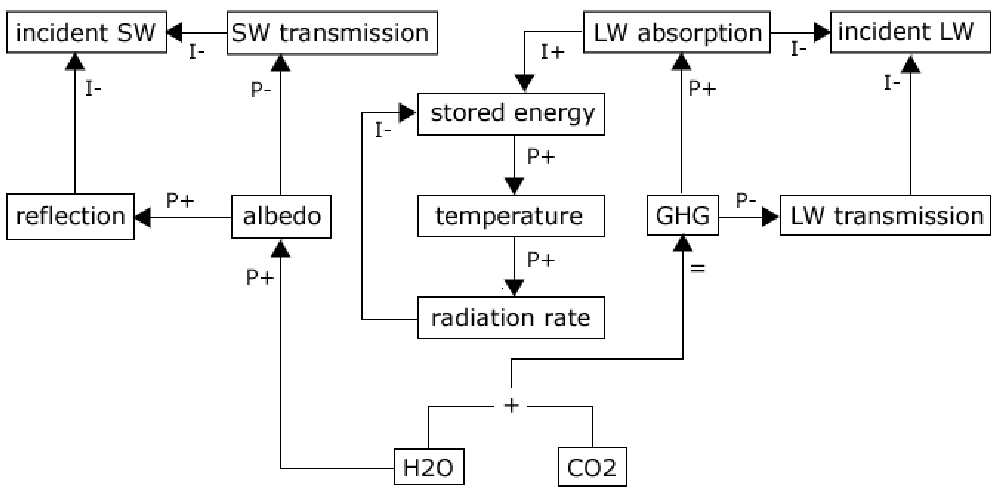

Figure 11: Atmosphere view

In turn, the albedo is determined (proportionally) by the amount of water vapour, as this represents clouds, which are reflective. Together with CO2, H2O determines the amount of greenhouse gases in the atmosphere. Greenhouse gases play a similar role in the atmosphere as albedo does, for this quantity determines what happens to incident LW energy. If the amount of greenhouse gases increases, the LW absorption rate increases, and LW transmission decreases proportionally.

Earth View

The earth has only one distinctive quantity besides the quantities it inherits from the object class ('table' 3).

Table 3: Earth quantities

Quantity	Quantity space
SW absorption	{zero,plus,max}

The earth (figure 12) can absorb short wave energy if it has a non-reflecting surface, i.e. the albedo does not have the value maximum. The albedo of the earth is determined by the substances at the surface, as is discussed in chapter two.

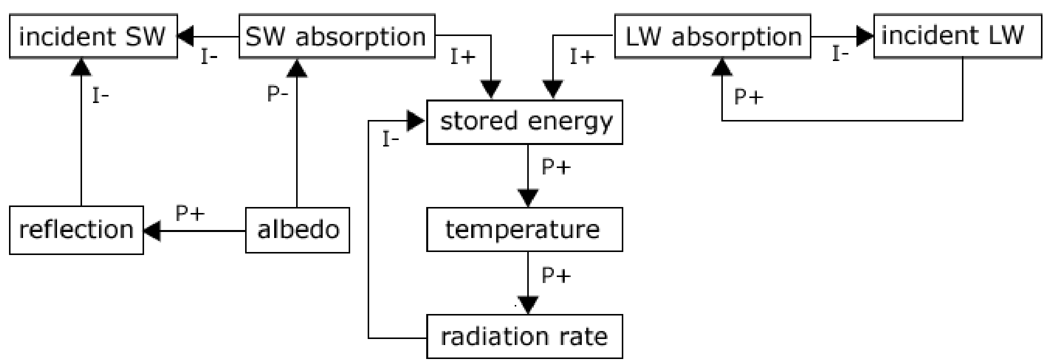

Figure 12: Earth view

The incident SW that is absorbed represents the first energy source of the earth, the sun. The absorption of LW energy represents the energy from the greenhouse gases. One important assumption is made concerning the absorption rate of long wave energy. Not knowing what the influences are on the absorption of long wave energy, I have made the assumption that, as there is more incident LW on the object, the LW absorption rate increases, i.e. incident LW has a positive proportionality relation with LW absorption.

Space view

The entity space (figure 13) is classified as *object* to inherit the quantities incident SW and incident LW, but the other quantities it inherits do not really belong to space. The classification of space as an object facilitates the modelling of certain processes at a more general level, as will be shown in the implementation section.

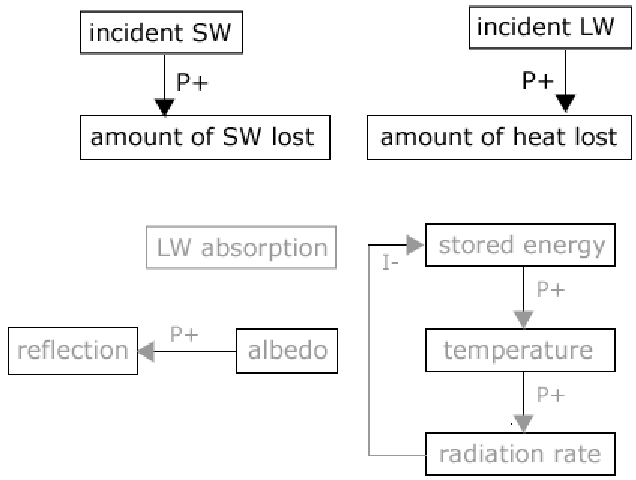

Figure 13: Space view

Space can be seen as a container for the radiation (short wave and long wave) that leaves the earth-atmosphere system. All long and short wave energy that enters space is either heat or light that is lost from the system.

3.2.3 Causal Structure of the Greenhouse Domain

All objects put together within the structure illustrated in figure 2, enables the global causal structure where the influences between objects and quantities can be demonstrated (figure 14).

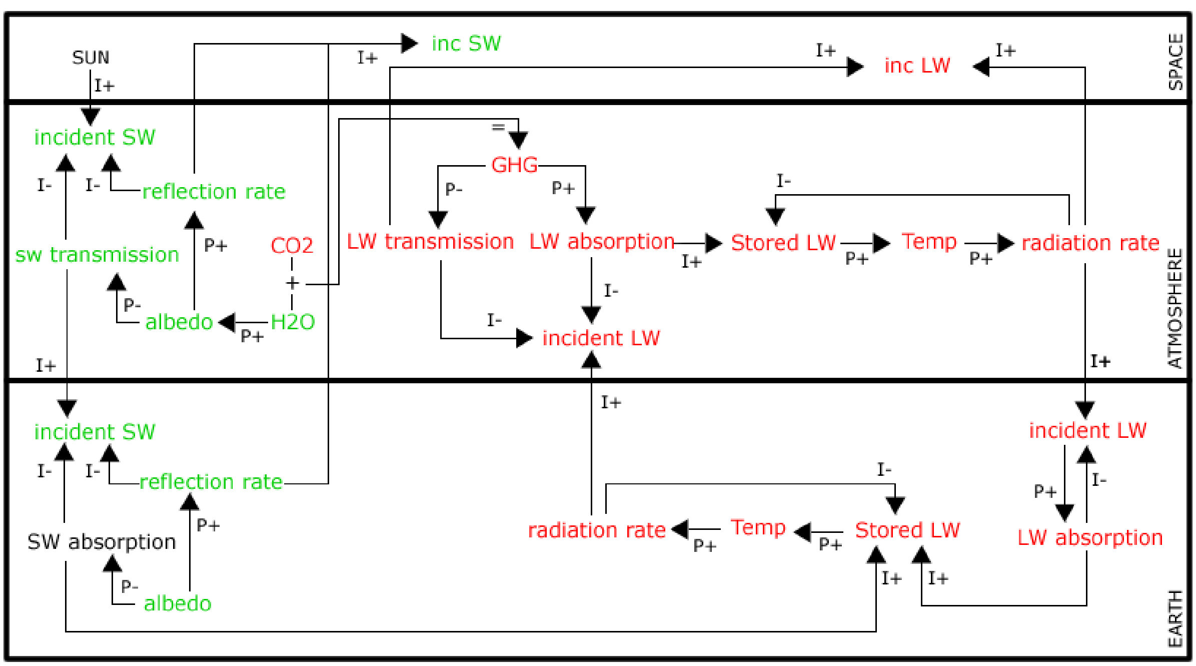

Figure 14: Causal structure of the greenhouse domain. Quantities in red represent the long wave energy flow, green quantities represent the short wave radiation flow.

Starting in the upper left corner, the sun radiates short wave energy onto the atmosphere. The albedo of the atmosphere determines whether this energy is reflected to space or transmitted to earth. If this short wave energy reaches the surface of the earth, the earth's albedo determines the ratio between SW absorption and reflection. If the energy is reflected the short wave energy is directly transported to space, if it is absorbed it is stored in the earth as long wave energy. As described in the object view, stored energy determines the temperature, which in turn determines the radiation rate. Energy radiated by the earth reaches the atmosphere, where greenhouse gasses determine what happens to this energy. If greenhouse gasses are present, part, or all incident LW energy is absorbed, and consequently store in the atmosphere. Absence of greenhouse gasses facilitates the transmission of long wave energy to space. Stored energy in the atmosphere is both radiated to space as to earth, where this energy is absorbed by the LW absorption process.

3.3 Implementation

The GARP[7] simulation engine is used to simulate the qualitative model that is constructed. GARP takes as input a library of model fragments and input scenarios to simulate behaviour represented in the model fragments. With the model-building tool Homer, a qualitative model is constructed that can be simulated in GARP. The output of GARP is visualized in VisiGarp[8].

Using the specified building blocks from the conceptual model, the library of model fragments and scenarios can be implemented. Model fragments represent *knowledge chunks.* A guideline for the construction of model fragments is that each relevant domain concept should be expressed in a single model fragment (MF). In this section, a few of the most important model fragments and modelling decisions are discussed, illustrated by screen dumps from Homer[9].

3.3.1 Static Model Fragments

In this section, the static model fragments are described. Static model fragments represent entities and their characteristics and dependencies.

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[7] http://web.swi.psy.uva.nl/projects/GARP/GARP/garp.html

[8] VisiGarp is a graphical user interface for Garp. http://web.swi.psy.uva.nl/projects/GARP/VISIGARP/visigarp.html

[9] For an extended legend and overview of homer, see http://web.swi.psy.uva.nl/projects/GARP/HOMER/homer.html

Object

In line with the conceptual representation, object has the quantities as shown in figure 15. If the entity *object* is used anywhere in the model, all of these quantities apply. Besides the proportionality relations between stored energy, temperature and radiation, correspondence relations are added, representing the fact that values of quantities are transported to the next quantity, i.e. if the temperature has the value max, so will radiation. No direction in this correspondence relation is given, as this does not represent actual causal behaviour. Thus if a value for stored energy is known, the values for temperature and radiation are also known.

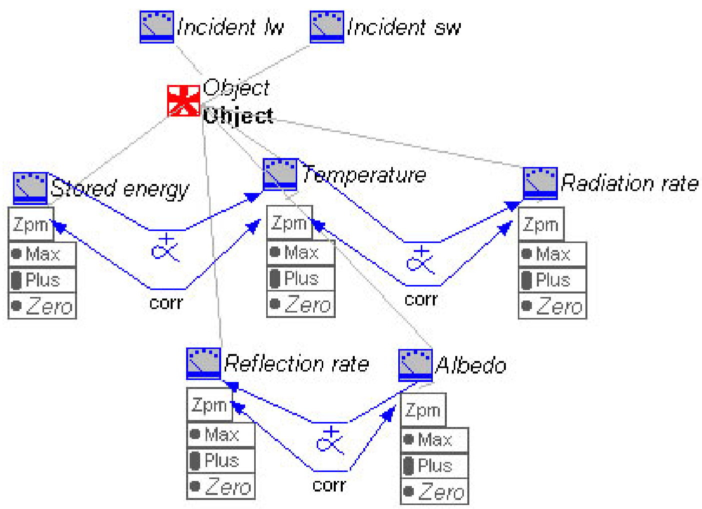

Figure 15: Object

The proportionalities and correspondences within an object represent a kind of *mythical causality* (de kleer & brown). This means there some sort of causality that determines the vales of corresponding quantities without the influence of processes. If one chooses to model a more detailed view of what happens inside if the object, ad answer questions as to why the temperature rises, one should model processes and influences that show that causal behaviour.

Object: Earth

Earth, being a subtype of object, inherits all the quantities from the entity object (figure 16, indicated by the grey/green coloured quantities. Note that some are hidden). For earth, some additional characteristics are added (blue/green quantities). The entity earth is connected with the entity object trough an identity relation, this implies that both entities are actually the same (i.e. have the same identity).

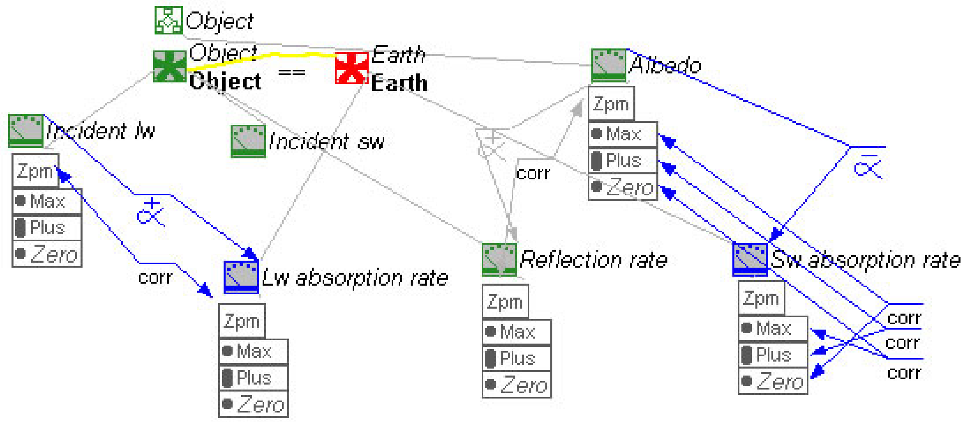

Figure 16: Earth

In this model, most proportionality relations are supported by correspondences to reduce ambiguity in behaviour. As albedo determines the processes reflection and SW absorption, it also determines the values of these processes. All the values of albedo are transported to the reflection rate by a full correspondence, and the opposite values are transported to SW absorption (i.e. value max of albedo is connected to the value zero of SW absorption). The relation between incident LW and LW absorption on earth represents the assumption that, independent of any other quantities, all LW energy on the surface is absorbed, the rate being determined by the amount of energy.

Object: **Atmosphere**

The atmosphere model fragment is slightly more complicated (figure 17). Albedo is modelled in the same way as in the earth model fragment, with the exception that the correspondence that transports the reversed values does so with the processes SW transmission, instead of SW absorption in the earth model fragment. Greenhouse gases are connected to the processes LW absorption and LW transmission in the same way as albedo to its corresponding processes. Not visible in this figure is the correspondence relation between H2O and albedo. As the amount of water vapour in the atmosphere increases, so does the albedo. There is no real casual relation here; the values of H2O just determine the values of albedo. The addition of H2O and CO2 determines the value of GHG, as is represented by the calculus (plus sign).

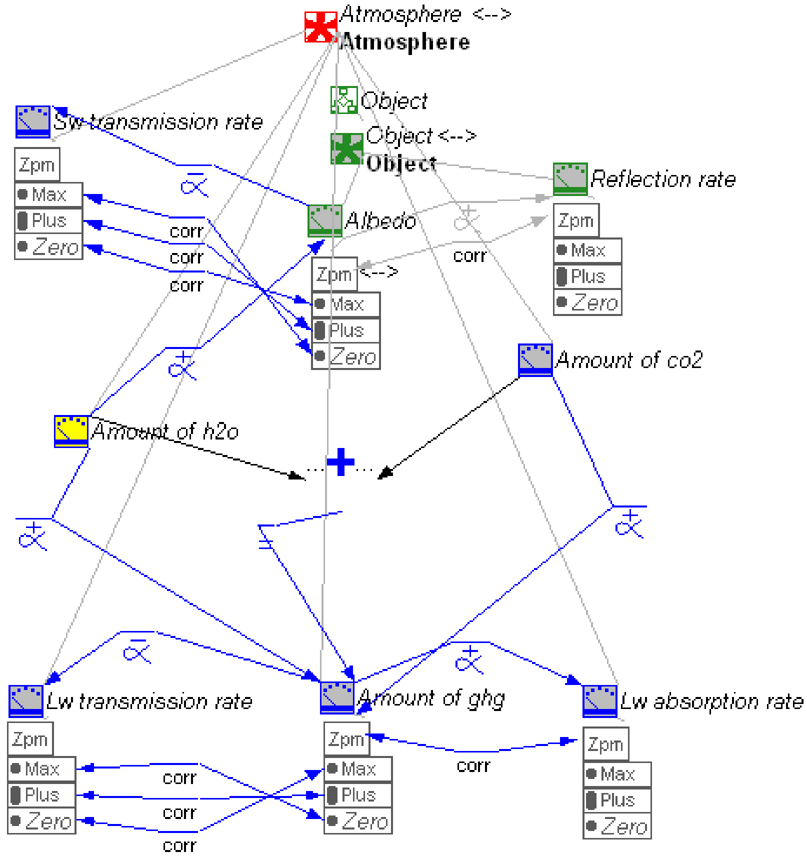

Figure 17: Atmosphere

Earth: **Radiative balance**

To determine the radiative balance of the earth, a model fragment is constructed that determines the derivative of temperature. For this concept, three model fragments are used that show whether the earth is cooling, warming or has a steady temperature. In figure 18, the last situation is illustrated. If the LW and SW absorption rates together have a value that is equal to the radiation rate, the temperature will keep its value (represented by the value {zero} of its derivative), i.e. it does not increase or decrease. This describes the situation that the amount of incoming energy equals the amount of outgoing energy.

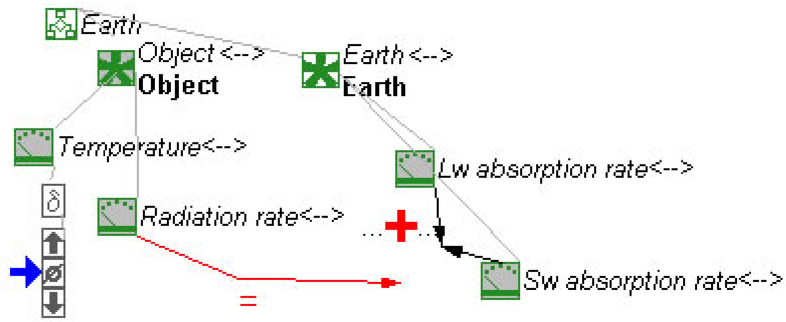

Figure 18: Derivative of temperature

The other two model fragments for the derivative of temperature describe the situations where the adding of the absorption rates is either smaller then the radiation rate (leading to the derivative plus of temperature) or greater then the radiation rate (determining the derivative of temperature to be min).

Earth: Determining the number of heat sources

To illustrate the Greenhouse effect, seven model fragments are constructed that describe distinct situations where the earth has either one or two absorption rates, or combinations of the values of the two rates. Depending on the presence or absence of these heat sources, an upper boundary for temperature is determined. This is illustrated by figure 19. In this model fragment, the earth gets input from one heat source, the sun (LW absorption rate is equal to zero). If there is only SW absorption, the maximum temperature can be either zero or plus, but not max. The only situation where temperature can get a maximum value is when both absorption rates reach the value max (figure 20). This situation represents the idea that when there is an increase in greenhouse gases to values that are above normal (i.e. normal is represented by the value plus), the temperature can reach values that are higher then in a normal situation.

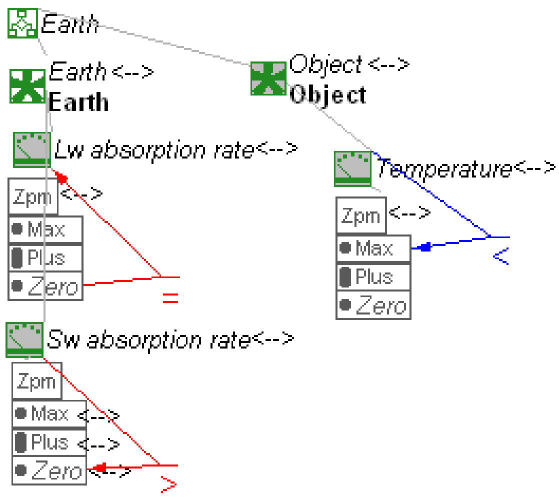

Figure 19: Earth with one heat source, the sun

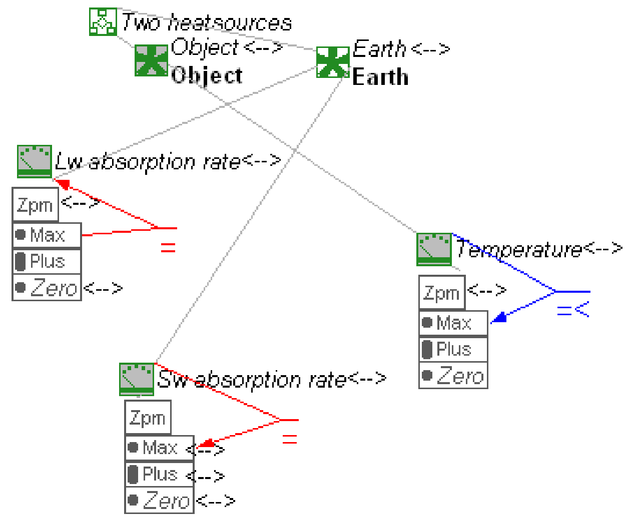

Figure 20: Two heat sources, both max

3.3.2 Processes

Process model fragments describe influences between quantities when certain conditions are met.

Radiation

Radiation (figure 21) is modelled at the *object level*. There are three conditions that must be true before this process is started (conditions are in red). There must be a radiating object, i.e. there must be an object with a temperature above zero, there must be some other object that is connected to the radiating object by a *radiation path,* and the receiving object must have the quantity inc LW. No conditions are set for the receiving object; this can be any object that has the quantity incident LW.

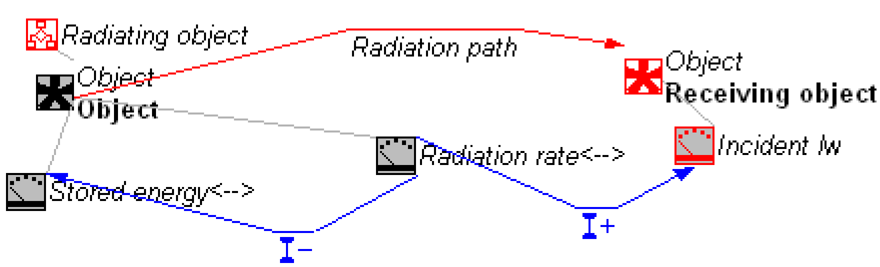

Figure 21: Radiation process

If these conditions are true, the process is started where the radiation rate negatively influences (represented by blue arrows) the stored energy of the radiating object, and positively influences the amount of incident LW of the receiving object. The radiation path, besides connecting the two objects, also determines the direction of the processes, which is, from the radiating object, to the receiving object. No conditions to the radiation rate are made, as the value of this process rate is determined by the temperature (see object model fragment).

Reflection

Conditional for the process reflection (figure 22), is a reflecting object, i.e. an object that has an albedo value above zero. In line with the previous process discussed, other conditions are that there is a receiving object (which can be any object), and a reflection path from the reflecting object to the receiving object. Additionally there has to be an amount of Inc SW present at the reflecting object (represented by the greater then zero relation for the quantity incident SW). If all these conditions are met, the reflection process has a negative influence of the incident SW and a positive influence on the incident SW of the receiving object.

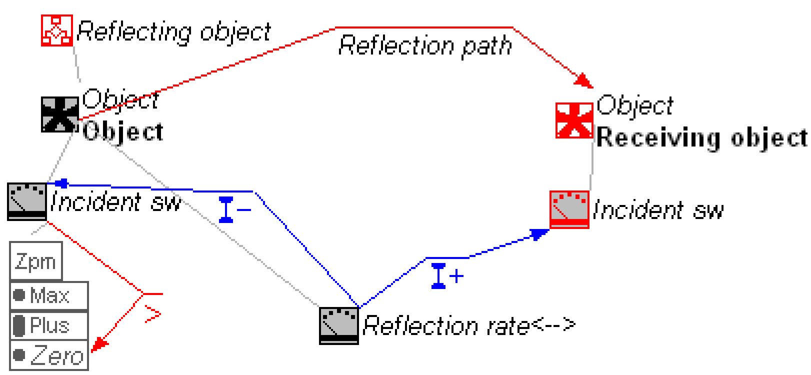

Figure 22: Reflection

Note that, for reflection and other processes that are described below, no condition is made as to what the value of the process rate should be. This is done because GARP has trouble determining what happens with a process if the rate happens to be zero. A requirement for the process to have a value of plus or max would require the additional process model fragment describing the 'opposite' of this process, i.e. modelling the no-reflection situation. The decision was made that all processes may fire, but in the situations where they have the value zero, they do not influence the relating quantities.

Long wave absorption

The absorption of long wave energy (figure 23) is a process that happens 'within' an object, or more specifically, is a process between the surface of an object and the inside of the object. If there is an object (any object) that has a LW absorption rate and an amount of incident long wave energy, then this process is started and positively influences the stored energy by negatively influencing the incident LW energy.

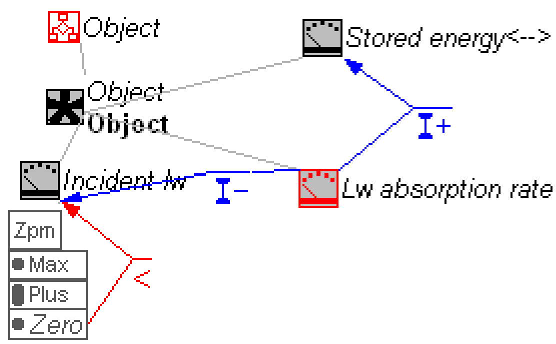

Figure 23: Long wave Absorption

The rate of LW absorption is determined in a different way for both the earth and the atmosphere, as discussed earlier.

Short wave absorption

As the earth is the only object that absorbs short wave radiation (figure 24) this process is modelled with the earth as a conditional model fragment. This process is started when there is an amount of inc short wave energy, after which the absorption process absorbs the inc energy and positively influences the amount of stored energy.

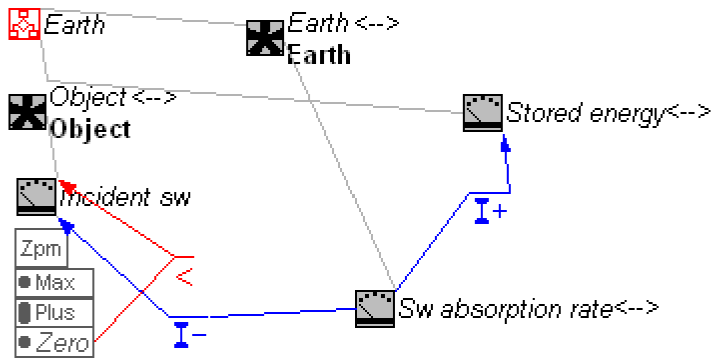

Figure 24: SW absorption

Fossil fuel burning

Fossil fuel burning (figure 25) requires the presence of industry that is connected by a CO2 exchange path with the atmosphere. When there is industry present, there is a fossil fuel burning rate that positively influences the amount of co2 in the atmosphere. This rate is determined by the static model fragment 'industry' which states that if there is industry, there is a fossil fuel burning rate with a value plus.

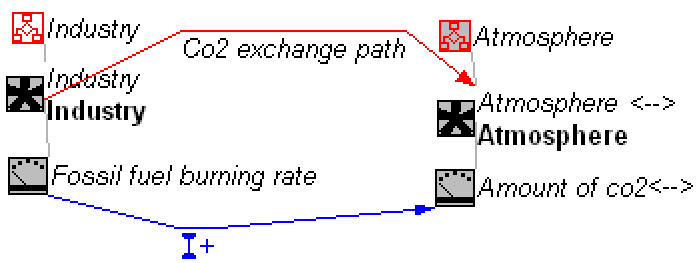

Figure 25: Fossil fuel burning process

3.4 Simulation

After the implementation of the model fragments describing the objects and processes, scenarios were constructed to function as input for the simulation engine. A scenario describes a situation of the system at a certain time. This description contains objects quantities with values and structural relations between objects. When a scenario is loaded, GARP tries to find all the relevant model fragments find all the possible states in a causal order that can be deducted from this initial state described in the scenario. Thus, scenarios are structural descriptions of the system of which GARP simulates the subsequent behaviour. The construction of scenarios requires some effort and overview of the system to introduce a *valid* initial state, i.e. a state that does not introduce conflicts in values so that GARP cannot find model fragments that apply to this scenario.

As described in Chapter 2, the aim was to construct three scenarios that could simulate the behaviour of the system influenced by industrial CO_2 emissions and wood burning/cutting rates and a volcanic eruption. Before discussing one of the implemented scenarios, it should be made clear that the modelling process was more complicate than first anticipated. To have the simulation show a rise in temperature of the earth by increasing the greenhouse gasses in the atmosphere could only be accomplished for a small part, below it will be explained why. First, a simple scenario describing the earth radiating to the atmosphere is described to illustrate the simulation process.

Earth radiation scenario

To test whether the modelled processes showed the perceived behaviour, some scenarios were constructed that focus entirely on one process. Below (figure 26) the scenario for earth radiation is described. For radiation to start a radiating object is needed that is connected with some other object through a radiation path, and the receiving object should have the quantity incident LW. Introducing the entity *earth* in the scenario will have all the quantities in the earth model fragment become active. As earth is an object, and all objects have the proportional and correspondence relations between stored energy, temperature and radiation rate, this will make this knowledge *active* as well. Knowing the value for stored energy, the values for temperature and radiation rate are also known. This creates the situation were introducing an object with an amount of store energy above the value zero, becomes a radiative object.

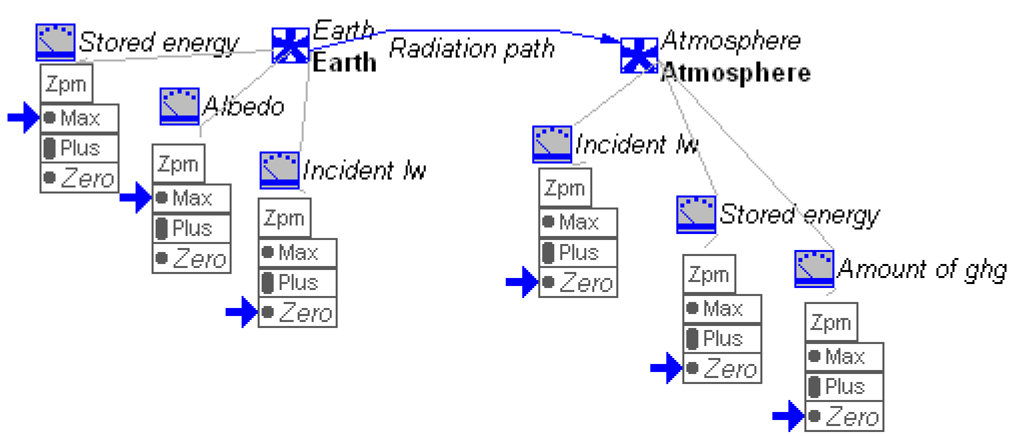

Figure 26: Earth radiation scenario

The atmosphere entity in the scenario has been given values for stored energy and greenhouse gasses to have GARP start the simulation with only one begin state. It is necessary to set values for determining quantities belonging to the objects. If one does not, GARP will assume values for the unspecified quantities and this may introduce unnecessary ambiguous behaviour. In this scenario, the values of the quantities that do not play a role in the desired behaviour are set to zero. The value zero for greenhouse gases determines the value {zero} for LW absorption and value {max} for LW transmission, but as there is not transmission path, this process will not become active. The LW absorption and SW absorption processes are also turned off to exclude these processes from influencing the amount of stored energy. Goal of this scenario is to have the radiation process radiate all stored energy and transfer this energy to the surface of the atmosphere (incident LW).

The input scenario constructed in Homer is imported in VisiGarp to simulate and visually inspect the simulation results. GARP generates all the states in a causal order that it can derive from the input scenario. From the earth radiation scenario, GARP deduces a state transition as is shown in figure 27. The circles represent distinct states of the system, and the arrows between states show the possible transitions between states. As can be seen in figure 23, state 1 generates 3 options for possible transitions, this can be seen as ambiguity in behaviour, if GARP does not have enough information to determine the precise transition of states, it generates all possible options. In this figure, it means there is some ambiguity in the model that causes state one to have three succeeding transitions.

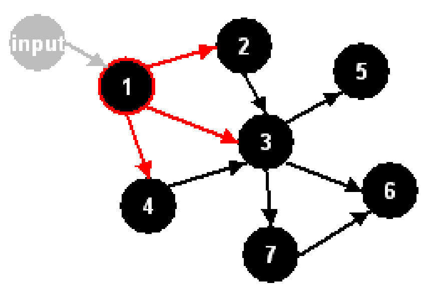

Figure 27: Earth radiation state transition

In figure 28, the active model fragments in state 1 are shown. The model fragment 'object' is shown twice, once for earth and once for atmosphere, as well as the both model fragments for these objects. The earth is a radiating object because it has stored energy, and it is a reflector for it has a value {max} for albedo (though the reflection process is not started, as there is no reflection path and incident SW energy). As can be seen by the list of active model fragments (figure 28) the atmosphere has a steady temperature and the earth is cooling.

```
object(atmosphere)
atmosphere(atmosphere)
object(earth)
earth(earth)
radiating_object(earth)
reflecting_object(earth)
radiation((earth, atmosphere))
atmos_steady_temp(atmosphere)
earth_cooling(earth)
sw_absorption(earth)
```

Figure28: Active model fragments in state 1

The dependencies between the quantities of state 3 are shown in figure 29. It illustrates the causality in state 3. As the earth is radiating energy, the negative influence on the amount of stored energy causes this quantity to decrease. The proportionality relations transport this value to temperature and radiation rate. The positive influence of radiation rate on the amount of incident LW in the atmosphere causes this quantity to increase. In addition, as there is no absorption rate in the atmosphere (because of the absence of greenhouse gases) the stored energy in the atmosphere does not increase.

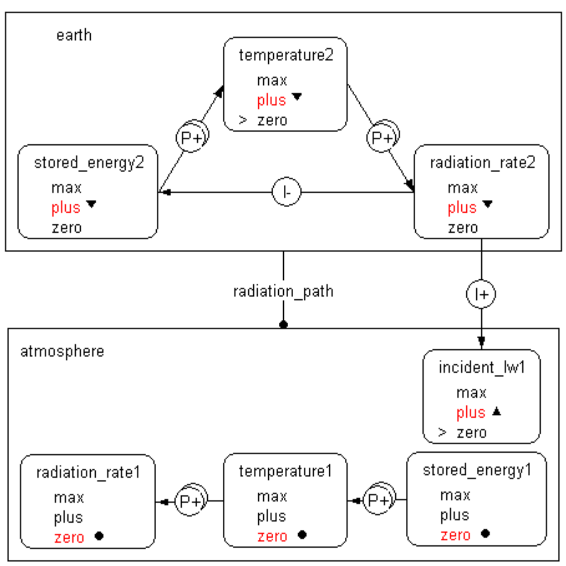

Figure 29: Dependencies in state 3.

In Visigarp, the value history of quantities can be inspected to see how the values of quantities are changing after each state transition; this is illustrated by figure 30.

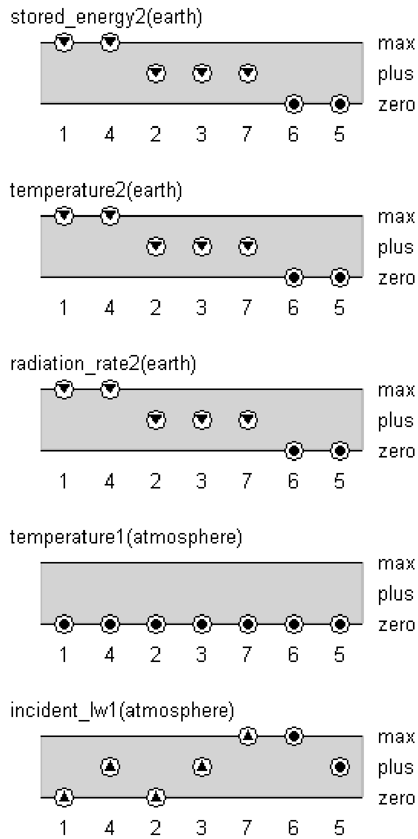

Figure 30: Value history earth radiation

For each state transition (figure 27) the values and derivatives of the quantities are drawn. In figure 30, the quantities relevant for earth radiation are selected. The numbers at the bottom of the quantities represent the states, the circles represent the value and the way the circles are filled represent the value and the derivative of the value (i.e. a completely filled value represents a derivative of zero, downward triangle the derivative min, and an upwards triangle the derivative plus).

Starting with the values from the scenario, GARP finds the derivative of each of those values. In this example, it can be seen that even though each value and its derivative are known, the model does not provide enough information as to how the values should change in the next state transition. State 1 has three possible state transitions, state 2, 3 and 4. This ambiguity arises because GARP does not know in which order the quantities do actually change their values (for instance, go from max to plus). In this example the options are that either Incident LW changes its value first (from zero to plus), radiation rate and related quantities change their values first, or all quantities are given the next value simultaneously. Accepting this ambiguity, one can see that the global behaviour started with this scenario, corresponds with the conception of what should happen to the stored and incident energy. The earth radiates until it has radiated all of its stored energy, and all of this energy eventually becomes incident on the atmosphere.

This simple scenario shows that modelling an energy flow without inequalities requires means of reducing the ambiguity in determination of what happens to the values of the corresponding energy 'storages' in the connected objects. The idea that, as one 'package of energy' is radiated, it leaves the first object and reaches the second, which leads to a decrease of stored energy in object A and an increase of inc LW in object B, is not modelled explicitly and therefore creates ambiguity in the determination of the values of the state transitions.

Scenario: radiation cycle empty atmosphere

Next, a more complicated scenario is discussed (figure 31). This scenario represents the radiation cycle with an empty atmosphere, i.e. an atmosphere that does not contain water vapour or carbon dioxide. It shows the successive processes:
solar radiation --> full transmission A --> full absorption E --> radiation E --> full transmission A --> space.

The absence of gases means the atmosphere is fully transmissive for both incoming sunlight and outgoing long wave radiation. The empty atmosphere is represented by giving the quantities stored energy, GHG, and albedo the value {zero}. Solar radiation, with a constant radiation rate of {plus}, enters the atmosphere by means of the radiation path.

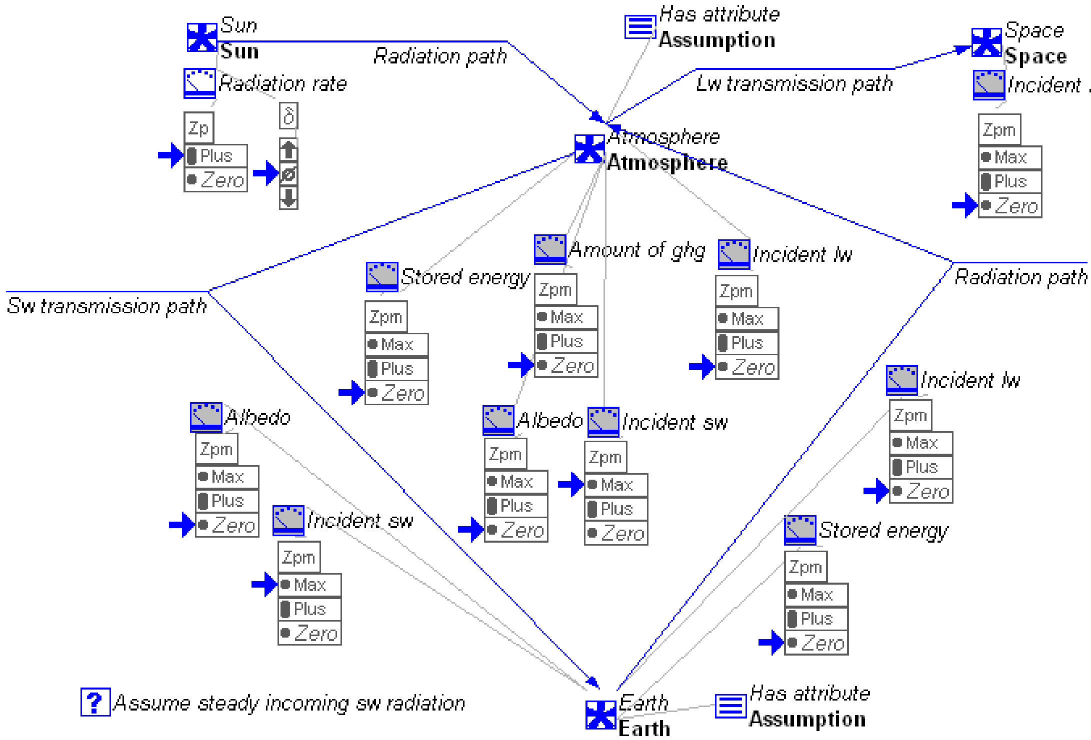

Figure 31: Empty atmosphere scenario (GHE 03)

The incident SW in the atmosphere is transmitted to earth, which in turn absorbs all of this energy (represented by the value {zero} for albedo that determines the value for SW absorption). This absorption process increases the amount of stored energy in the earth, which then is radiated to the atmosphere. As the atmosphere does not contain any greenhouse gases, it transmits all of this incident LW energy to space by means of the LW transmission path.

The continuous stream of incoming short wave energy is represented by the assumption 'assume steady incoming SW radiation' (figure 32). This assumption describes the idea that if there is solar radiation, the incident SW in the atmosphere has the derivative {zero}. This does not apply to all situations, but only becomes active if the assumption is explicitly introduced in the scenario (as is done in scenario GHE 03). The attribute 'assumption' of atmosphere is constructed to specify that this assumption applies to the atmosphere, as the same assumption can be used in another model fragment that describes the same knowledge for earth. The assumption for earth states that if the atmosphere is fully transmissive, the derivative of incident SW earth is {zero}, thus this value does not change. Both assumptions represent the fact that as long as the sun shines there will be incident SW energy in the atmosphere and/or earth.

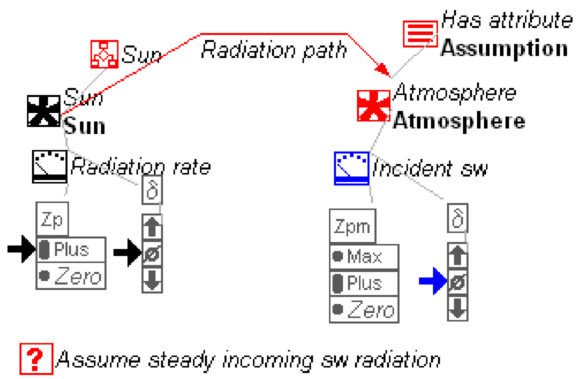

Figure 32: Assumption steady incoming incident SW atmosphere

Running the empty atmosphere scenario in VisiGarp generates the following state transition (figure 33).

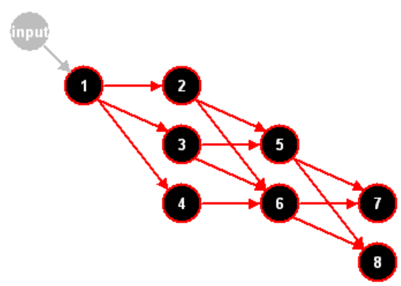

Figure 33: State transition empty atmosphere scenario

The value history (figure 34) shows that the first five quantities have values that remain the same in all states, as explained earlier. One remark should be made here. If the sun should stop shining and the atmosphere has an albedo with the value zero, the SW transmission rate would still have the value {max}, even though it would not actually *run*, this is because the values are fixed in the model fragment atmosphere (the same remark applies to the model fragment describing the earth). The second thing that can be noticed in this overview is that the stored energy, and therefore the temperature (not shown in the picture) and the radiation rate do not become {max}. The cause for this is the restraint in the model fragment determining the upper boundary for earth temperature when there is one heat source, in this case only the sun (see figure 19).

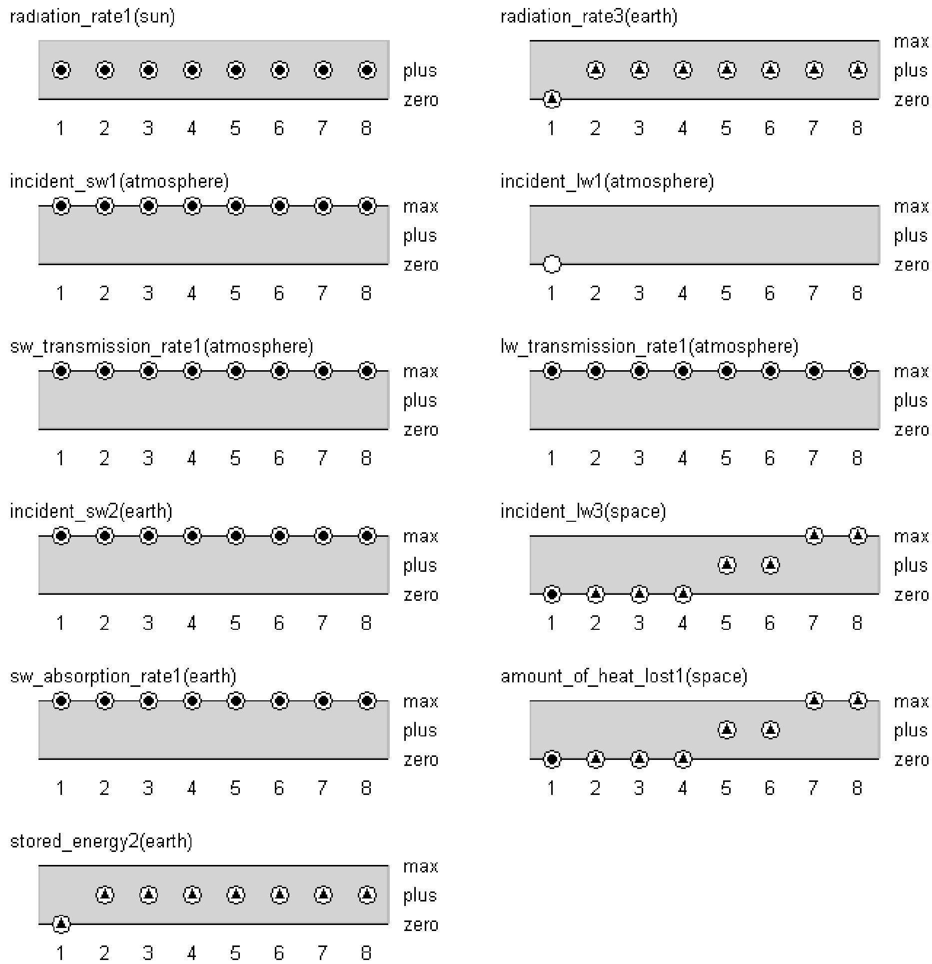

Figure 34: Value history empty atmosphere scenario

Because of the limitations in time to finish this project, it remains unclear why GARP does not find any value for incident LW in the atmosphere besides the one given in the scenario. Because GARP simply assumes a value (in this case {plus}) this could have an undesired effect on the behaviour of the model. In this particular case, the reason that this value remains left open could be the difficulty in determining the value because the two processes LW transmission and earth radiation are both simultaneously influencing the quantity in opposite directions. In this particular example, the assumption of the value plus by GARP did not create undesired behaviour. As the atmosphere transmits all incident LW energy, the heat lost to space increases. The causal path is shown in figure 35 (the representation in VisiGarp is not optimal; therefore the radiation path from earth to atmosphere is not visible, for it is hidden under the SW transmission path).

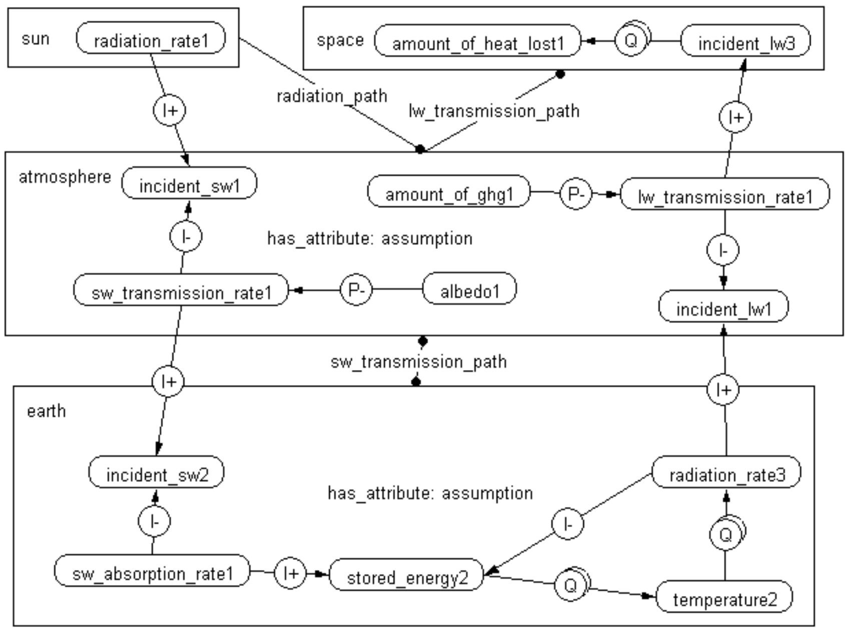

Figure 35: Causal path of the empty atmosphere scenario

An attempt to simulate the Greenhouse effect is shown in figure 36, where the initial empty atmosphere should become more and more absorptive of long wave radiation due to fossil fuel burning by the industry, which increases the amount of CO_2 in the atmosphere.

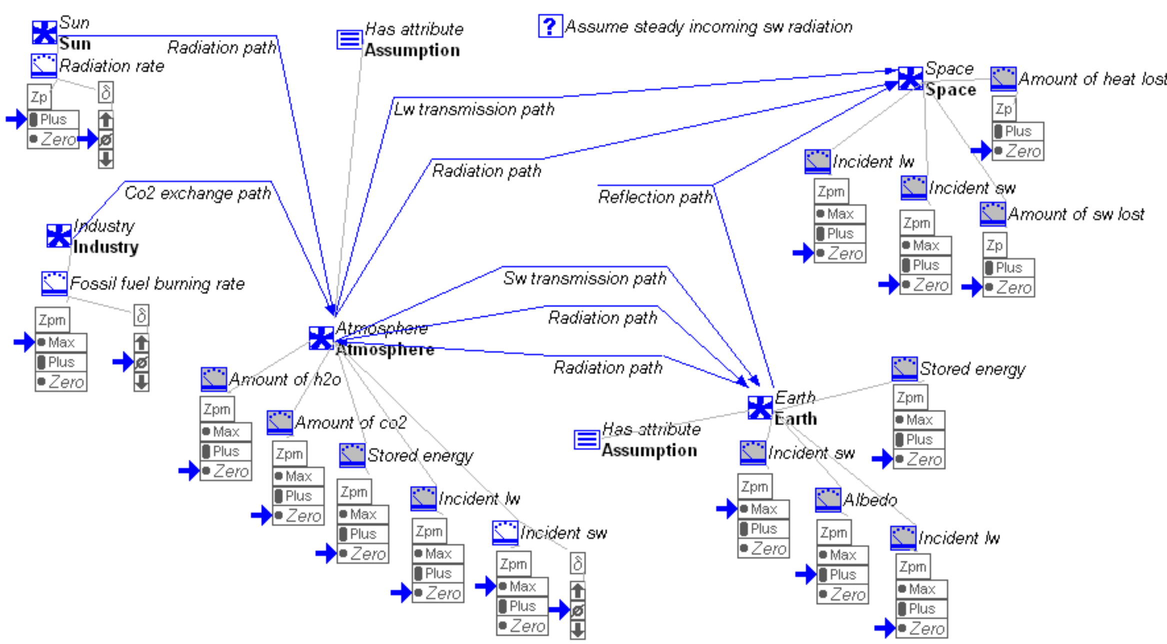

Figure 36: Scenario with fossil fuel burning

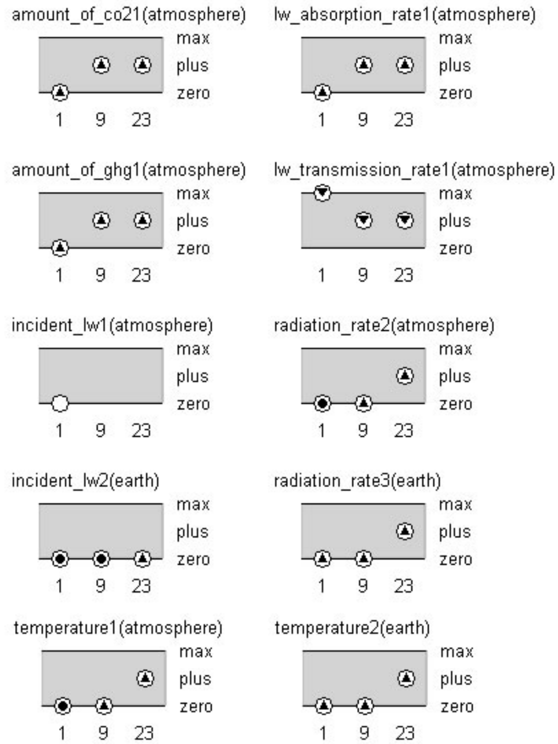

Figure 37: Three state transitions in the Fossil fuel burning scenario

This proved to be quite problematic. The first termination (state transitions leaving from state one) resulted in so many subsequent states (16) it was quite clear there was too much ambiguity in the model. Because of a lack in processing power only three states were terminated to see whether at least some of the intended behaviour was being simulated, and it turned out this was the case as can be seen in figure 37.

What the model shows nicely is that the increase in CO2 in the atmosphere increases the LW absorption rate and decreases the LW transmission rate. In addition, as the earth becomes warmer through the absorption of short wave energy this leads to an increase in the temperature of the atmosphere as this is able to absorb the incident energy in state 9. Moreover, although not actually increasing, the derivative of stored energy in state 23 of the earth shows that the radiation of the atmosphere to the earth is functioning more or les. Further simulation was not possible due to lacking processing power and time.

3.5 Evaluation

A domain and qualitative modelling expert evaluated the model discussed in this chapter. In this section, the expert's comments are summarized. Overall, the expert believed that the models' ambiguity was not a matter of adding details and specifications, but of focussing on certain processes and excluding the rest. The most important issues in the Greenhouse effect are the influences of long wave energy and CO_2 on global temperatures. By excluding some processes, some quantity spaces can be expanded to capture states that are more detailed. Additionally, certain quantities, as for instance incident SW and incident LW, can be given the quantity space {plus} as these quantities are always present. Processes are sufficiently specified by a quantity space {zero,plus} because the value {max} does not have a real meaning for these processes. Moreover, some processes could be excluded from the model all together. For instance, 'long wave absorption' can be represented by a proportionality relation between incident LW and stored LW to make the model simpler. To have students understand the Greenhouse effect at an introductory level, the expert agreed that representing the radiation cycle by means of a heat flow is indeed not necessary, and the knowledge capture by this model comes close to the way the Greenhouse effect is taught in an introductory course.

3.6 Discussion & Conclusion

As discussed in the first chapter, interaction with qualitative simulation can be a valuable learning tool. To enable the use of qualitative simulation models for educational purposes, more models are needed from domains other then the physics domain. For this reason, this thesis introduces an effort in constructing a qualitative model of the Greenhouse effect.

The research discussed in this thesis, is a first exploration of qualitative modelling in the domain of the Greenhouse effect. To our knowledge, no other qualitative models have been constructed in this domain. Some issues discussed in this paper address problems that have not been encountered by qualitative reasoning research before.

Constructing a model of the Greenhouse effect requires a way to represent stuff (radiation) that goes *through* an object. In the literature on Qualitative reasoning, many examples are found of liquids and gases inside containers and flowing between containers, but no representations to describe how to model such a situation. The model described in this thesis, does not represent this situation explicitly. An object simply transmits energy from its surface to the surface of another object.

Another issue was to find a way to represent how a single energy flow is divided into different flows after interaction with an object or process (figure 38).

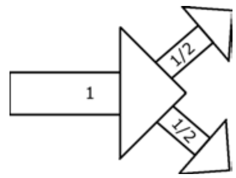

Figure 38: Division of flows

For example, the fact that of all the incoming short wave radiation from the sun, 25% gets reflected in the atmosphere, which leaves 75% of the short wave radiation to be disseminated by other processes. A way to resolve this is for instance the use of quantity spaces that contain values like {half} or {total}. The domain expert proposed to leave this division implicit. As the flows of energy are continuous there is always *some* energy present, and therefore quantity spaces with the value {plus} will suffice. In this model, the quantity spaces {zero,plus,max} are used to represent exaggerated situations that do not exist in the 'real world' but are needed to explain certain phenomena, as described earlier.

With a domain as complex as the Greenhouse effect, determining the *scope* and *abstraction level* of the model requires considerable effort and knowledge of a domain. Although the intention was to capture the basic knowledge of the Greenhouse effect in a simple model, it turned out that is was not possible to realise that. Not only are the phenomena in the Greenhouse domain inherently complex, it was also necessary to add additional constraints to the model in order to keep the simulation manageable.

As this research is concerned with the implementation of domain knowledge in a qualitative simulation model, done by a single person, it is not possible to construct an evaluation by means of an experiment, as in this research the model builder and evaluator are the same person. Future research of the construction of a framework for evaluation of qualitative models will be very helpful in adding to the understanding of what is needed to construct this type of models. See for an example of a case study about the learning effects of model building, Salles & Bredeweg (2003).

The model presented in this thesis, is based on knowledge found in textbooks and scientific publications about the Greenhouse effect. A domain expert has reviewed the resulting model. Although the expert agreed on the way the knowledge was captured in the model, the expert also pointed out alternative views and simplifications to improve the current model. Future efforts to model the Greenhouse effect qualitatively can gain from consulting different experts and use that information to further refine the model to capture alternative views on the problem and using assumptions as a means to index and distinguish competing knowledge in the library.

Future research can investigate the issues discussed in this paper, to increase awareness about the requirements for modeling ecological domains for educational purposes.

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