Qualitative Models of Global Warming Amplifiers

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Abstract

There is growing interest from ecological experts to create qualitative models of phenomena for which numerical information is sparse or missing. We present a number of successful models in the field of environmental science, namely, the domain of global warming. The motivation behind the effort is to enrich the DynaLearn interactive learning environment model repository. We first model two of the negative feedback factors (snow and ice albedo and cooling aerosols), then two of the positive feedback ones (water vapor and warming aerosols). We then combine the two mechanisms in a larger model (low and high clouds), proving the possibility of extracting general mechanisms that can be reapplied to other systems sharing similar characteristics. Two field experts have evaluated the results.

Introduction

The DynaLearn project[1] develops an Interactive Learning Environment (ILE) that relies on Qualitative Reasoning (QR) methods to assist learners in constructing their conceptual system knowledge. The DynaLearn ILE gives learners automated feedback based on a comparison of their model to a set of expert-models stored in a repository. Therefore, a model repository is created that consists of a large set of small and easy to understand models.

We present models of five distinct phenomena. The domain of *global warming amplifiers* provides us with an opportunity to see two opposite feedback factors at work. The goal is to represent these factors in such a way that it becomes easy to extract the mechanisms and facilitate their reuse when modeling domains of similar characteristics using the DynaLearn ILE.

Qualitative Reasoning

An important power of QR lies in the ability to capture both structural and behavioral information, including the notion of causality. Garp3 provides a workbench that allows users to build, simulate, and inspect qualitative knowledge (Bredeweg et al. 2009). An important ingredient of a Garp3 model is the *Entity*, which can be arranged in a subtype hierarchy, and is used to represent the physical objects or abstract concepts the system itself is made of. The relevant properties that can change under the influence of processes are represented as *quantities*. *Agents* represent external entities that may influence the system's behavior, referred to as *exogenous quantities*. To indicate that certain conditions are presumed to be true, the modeler can use *Assumptions*. Their main use is to constrain the modeled system's behavior. Finally, *Configurations* represent the structural relationships between entities and agents.

Key aggregates are *Scenarios* and *Model fragments (MFs)*. Scenarios are used to represent a specific state the simulation may start from. MFs represent individual parts of knowledge about the system. When running a simulation for a given scenario, the QR engine searches the MF library to find the fragments that match the conditions given in that state. The end result is a state graph, which can be expected using multiple views, such as the value history and the causal model.

Global warming amplifiers

There is a growing concern about global warming and the impact it is expected to have on people and the ecosystems on which they depend (Haupt, Pasini, and Marzban 2008; Philander 2008; Lerner and Lerner 2009; Salles and Bredeweg 2006; Cioaca et al. 2009). Factors that can amplify or reduce the effect of the causes of climate change are known as *positive* and *negative feedbacks*, respectively. The four key feedback mechanisms[2] are the focus of the work presented here. The models provide abstract explanations. The envisioned end-user is a student looking to better understand the domain of global warming.

Planetary radiation balance and greenhouse effect The Earth's radiative energy balance depends on the balance between the incoming (shortwave) solar radiation and its absorption by the planet, and subsequent outgoing (longwave) radiation from the Earth to outer space (Philander 2008). The Earth emits the absorbed radiation from the Sun back to outer space maintaining its heat energy balance. The greenhouse gases, however, prevent the outgoing longwave radiation from leaving the atmosphere by absorbing it, and then

[1]The research presented here is co-funded by the EC within FP7 (2009-2012) (project DynaLearn, 231526, www.DynaLearn.eu).

[2]See e.g. www.koshland-science-museum.org

emitting it back toward the surface as shortwave radiation. This "surplus" in the planet's energy "budget" is what leads to global warming (Allaby 2000). This mechanism plays an important role in our positive feedback models.

Models of amplifiers

Snow and ice cover (SIC)

The *reflection coefficient* (*albedo* of a surface) is the proportion of light reflected by that surface. If the global warming reduces the global snow and ice cover, the warming will be enhanced because more solar energy will be absorbed. The snow and ice cover of the Earth's surface provide a negative feedback mechanism.

The entity hierarchy shown in Fig. 1 follows closely the Cyc concept hierarchy for the entities describing our domain. *Theearthsatmosphere* represents two concepts here – that of the lower part of the atmosphere and the Earth's surface. *Thesun* is the Earth's Sun, and the source of incoming solar radiation, *Planetearth* is our planet, and *Snow and ice cover* is the portion of the planetary surface covered by snow and ice. There is also a single agent, *Person*, see e.g. Fig. 5.

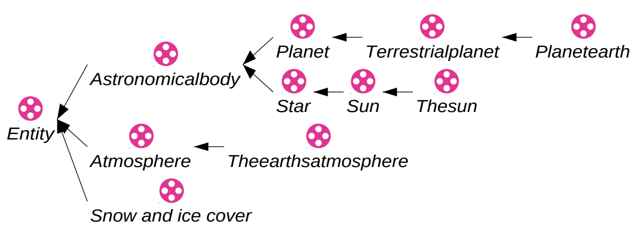

Figure 1: SIC: Entity hierarchy

Amount denotes the amount of snow and ice covering the Earth's surface, *Temperature* the Earth's temperature, and *Solar radiation* the incoming radiation from the Sun. To visualize the changes, we use a quantity space with three values {*low, medium, high*}. *Effective radiation* represents the total amount of radiation reaching the Earth's surface, i.e. the portion of incoming shortwave radiation that doesn't get reflected back to outer space. A quantity space with a negative value (*min*) is used to show opposite effects on global temperature. Finally, we use a quantity named *Greenhouse gases* for the amount of greenhouse gases emitted by the humans into the atmosphere. As with the effective radiation quantity, we use the {*min, zero, plus*} quantity space, so we can simulate the two-way effect on temperature (and, indirectly, snow and ice cover).

Our first global warming amplifier model contains one static, one process and one agent MF. The static MF is named *Snow and ice* (Fig. 2) and shows only that the snow and ice cover amount is indirectly influenced by the Earth's temperature.

The process MF, *Solar radiation reflectance* defines the incoming shortwave radiation reflectance by snow and ice mechanism.

We define the effective radiation magnitude as a balance, namely, the difference between the solar radiation and the

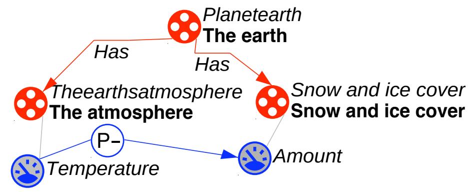

Figure 2: SIC: Snow and ice model fragment

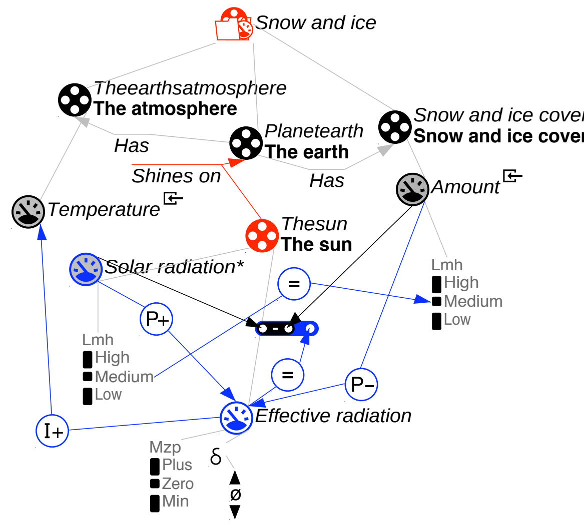

Figure 3: SIC: Solar radiation reflectance model fragment

amount of snow and ice covering the planet (Fig. 3). In order to be able to calculate the difference, we connect the two *medium* points using a *qualitative equality relation*. We also define a positive proportionality (P+) from solar radiation and a negative one from snow and ice cover amount to effective radiation, indicating that a potential increase in incoming radiation would result in an increase in effective radiation, and an increase in snow and ice cover would set the effective radiation to decrease. Finally, the Earth's temperature is directly and positively influenced (I+) by effective radiation. The single external (positive) influence on the global temperatures, provided by the greenhouse gases is defined in the *Humans* agent MF and shown in Fig. 4.

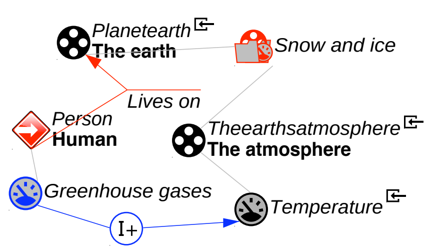

Figure 4: SIC: Agent model fragment

Scenarios and Simulation results The model has 5 scenarios: two showing the opposite effects of solar radiation, two for the same effects of greenhouse gases and one showing the balance between the snow and ice cover and the incoming solar radiation, if there are no disturbances. Fig. 5 depicts the *Increasing greenhouse gases* scenario, where the amount of snow and solar radiation are set to *medium*, the Earth's temperature to *low* (to clearly show the expected increase in temperature) and the amount of greenhouse gases being emitted into the atmosphere to zero. The solar radiation quantity here is set to be steady (it doesn't change throughout the simulation), but the greenhouse gases are set to increase. This way, the change in the system will depend only on the human influence.

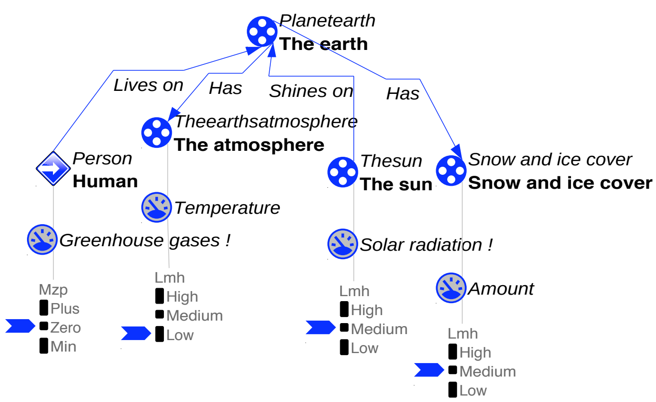

Figure 5: SIC: Increasing greenhouse gases scenario

The *Increasing greenhouse gases* scenario results in a linear path consisting of five states (Fig. 6). The value history (Fig. 7) shows that the magnitude of the planet's temperature increases with an increase in greenhouse gases. That is, as soon as the amount of greenhouse gases enters the *plus* interval (state 2), the balance is disturbed. Moreover, as the temperatures increase, they decrease the snow and ice cover, which further amplifies the increase in temperature as the effective radiation increases, even though the solar radiation is steady (states 2 to 5).

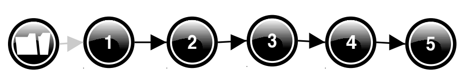

Figure 6: SIC: Increasing greenhouse gases state graph

The opposite effect can be shown using the same model. The magnitude of quantity *Greenhouse gases* of the external agent is then set to *min*, which causes the temperature to decrease (via the I+). The results show that the temperature drops and causes the snow and ice cover to increase, which further cools the Earth.

Cooling aerosols (CA)

Aerosols are solid or liquid particles, small enough to remain suspended in the atmosphere up to a number of days (Philander 2008). Although aerosols can affect the Earth's climate both directly, by the scattering or absorption of radiation, and indirectly, through the modification of clouds and

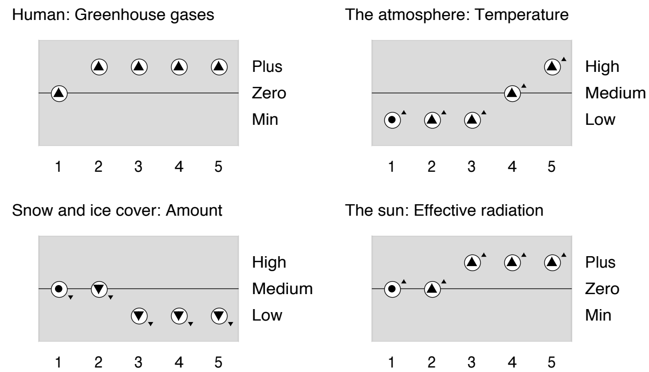

Figure 7: SIC: Increasing greenhouse gases value history

precipitation, we will be taking into consideration only the former effect.

The entity hierarchy is very similar to that of the first global warming amplifier model (Fig. 1). The only difference is in the bottom graph branch where the snow and ice cover entity has been replaced by *Cooling aerosols*, a child node of the *Gas* entity. The human being has a slightly different role in this model, as it is the chief factor controlling the aerosol amount in the atmosphere (the snow and ice cover amount was being governed by the Earth's temperature). The greenhouse gases quantity has been replaced with "human activity".

This model differs from the previous one in that the static MF this time has no direct or indirect influences defined, as the cooling aerosols have no direct relations to temperature. Instead, they're being controlled by the humans, as shown in Fig. 8, where there is a direct influence from human activity to the amount of cooling aerosols in the atmosphere. The *Solar radiation reflection* MF matches that of the snow and ice model (Fig. 3), being different only with respect to the right hand side of the effective radiation equation, where the *Snow and ice cover* entity has been replaced with the *Cooling aerosol* entity.

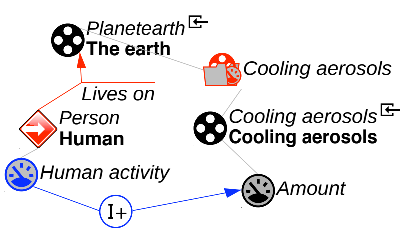

Figure 8: CA: Humans (agent) model fragment

Scenarios and Simulation results The four scenarios show the possible opposite effects of the two main factors on the system, i.e. solar radiation and the human activity. In the case of the two solar radiation scenarios, we set the cooling aerosol quantity to *steady*, as its magnitude and derivative depend only on external influences, but also in order to be able to see how the temperature behaves when only solar radiation changes. The other scenarios differ with respect to their snow and ice counterparts only in the choice of external influences, as explained earlier.

The simulation graph for the *Increasing human activity* scenario has 6 states. The value history shown in Fig. 9.

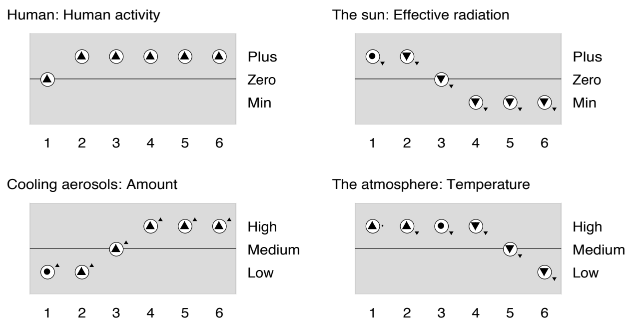

Figure 9: CA: Increasing human activity value history

In the first two states, the temperature is increasing. The reason for this is that the effective radiation is still in the positive interval. Once it hits zero (state 3) the temperature stabilizes, and next starts decreasing. This effect is due to the fact that there is only one influence affecting the aerosol amount, whereas in the snow and ice model, the temperature itself was a factor, influenced directly by two quantities.

Water vapor (WV)

The Earth's water present in the atmosphere (water vapor) is the most abundant and most important greenhouse gas on the planet (Lerner and Lerner 2009). Although the humans are not significantly increasing its concentration, at least not directly, it contributes to the enhanced greenhouse effect, because the warming influence of greenhouse gases leads to a positive water vapor feedback, which creates an enhanced greenhouse effect that increases temperatures further, and so on. The eventual runaway greenhouse effect is what is today believed to be the main reason why Venus has no water (Philander 2008).

In comparison with the *Cooling aerosols* model, the leaf node of the bottom branch has been replaced by the *Water vapor* entity.

The new model comes with three new quantities. The *Return radiation* quantity represents the amount of outgoing radiation that gets emitted back by water vapor, as explained in section "Planetary radiation balance and greenhouse effect". *OLR* is the Outgoing Longwave Radiation and *Total effective radiation* is the combined effect of incoming solar radiation and return radiation on the global temperature. For all new quantities, we use the quantity space {*min, zero, plus*}, so we can easily control the temperature (i.e. see it flow in both ways).

When compared to the *Snow and ice cover* and *Cooling aerosols* models, the first *positive feedback* model is based on a different mechanism, so its MF hierarchy is also different. We have one static MF, two processes and one agent MF. The static MF defines a positive proportionality between the global temperature and water vapor. It goes only one way, since the water vapor effect on temperature is indirect, as we will see in the process MFs.

The *OLR* and *OLR absorption* MFs define our planetary radiative energy balance mechanism and the creation of the surplus. The parent process, *OLR* shows how the OLR cools the Earth (Fig. 10). The amount of outgoing radiation equals that of the incoming one, and an increase in the incoming solar radiation results in an increase in the outgoing longwave radiation, due to the indirect positive proportionality between the two respective quantities. The negative influence from *OLR* to *Temperature* decreases the global temperature.

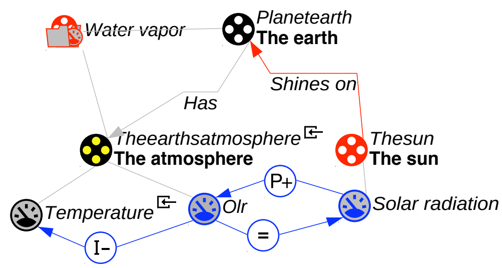

Figure 10: WV: OLR model fragment

The *OLR absorption* MF (Fig. 11) shows the second half of the balance mechanism, via the *Total effective radiation* quantity, which directly (positively) influences the planetary temperatures. The total effective radiation equals the sum of the solar radiation and return radiation emitted by water vapor. Therefore, if there is no water vapor in the atmosphere (i.e. the water vapor's *Amount* magnitude equals *zero*), the OLR compensates for the incoming solar radiation, and the system is at balance. However, the higher the amount of water vapor in the atmosphere, the greater the amount of return radiation, due to the equality and positive proportionality relationships; the quantity space correspondence relationship makes sure the magnitudes are always in the same interval. If the return or solar radiation increase, so will the total effective radiation influencing the temperature (due to the two positive proportionalities provided by their respective quantities and aimed at *Total effective radiation*).

Scenarios and Simulation results The *Increasing greenhouse gases* scenario is similar to the previously described ones. The *Greenhouse gases* quantity is set to *zero* and its behavior to increasing, *Temperature* to *low*, (water vapor) *Amount* to *zero*, and *Solar radiation* to *zero* (stable and constant). The solar radiation quantity's initial value is set to *zero* and its behavior to increase. The behavior of other quantities in the resulting two-state simulation graph shows the Earth's radiative energy balance mechanism at work. Only the solar radiation and the outgoing longwave radiation increase. The temperature remains stable, as expected. The Increasing greenhouse gases scenario, on the other hand, produces a 5-state graph. The rising amount of greenhouse gases in the air increases the temperature, which is the cause of higher levels of water vapor present in the atmosphere. As soon as the water vapor amount enters the positive interval

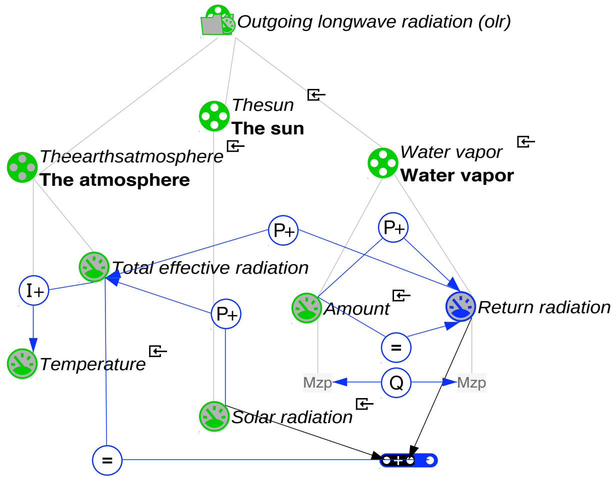

Figure 11: WV: OLR absorption model fragment

(state 3), the return radiation from this greenhouse gas ads to the total effective radiation, which provides the second direct influence on the global temperatures, and increases it further.

Warming aerosols (WA)

Although it is nowadays believed that the cooling effect of the aerosols in the atmosphere is dominant, the warming influence also leaves a significant mark on the global climate. Black carbon particles or *soot*, the coproduct of fossil fuel and vegetation burning, absorb and emit back the outgoing longwave radiation in the same way water vapor does (Staudt, Huddleston, and Kraucunas 2009). As with ice and snow albedo, the amount of water vapor both influences and strongly depends on the temperatures, whereas none of the aerosols have this relation to the planet's temperature.

The only new entity is *Warming aerosols*, which replaces the cooling aerosol / snow and ice cover / water vapor one in the bottom branch of the graph. The agent hierarchy remains the same. Compared to the previous model, the *Greenhouse gases* quantity is replaced by the quantity *Human activity*, a quantity corresponding to various human activities directly leading to increases and decreases in aerosol amount in the atmosphere. The positive feedback mechanism shown in Fig. 11 remains the same. The only notable difference is the RHS of the total effective radiation equation within the OLR absorption MF, where the water vapor entity has been replaced by warming aerosols. As described above, the external influence, i.e. the Human agent, provides a positive direct influence on the amount of aerosols.. Moreover, this is the only influence governing the aerosol amount in the atmosphere.

We keep the same number of scenarios and the basic ideas we've seen in the first positive feedback example (section "Water vapor"), only this time the external influence is different (human activity). The increasing exogenous behavior set for the human agent activity in the *Increasing human activity* scenario, produces a similar behavior as seen in the previous positive feedback model (Water vapor). However, as with the cooling aerosols, we have only one positive influence affecting the amount of our greenhouse gas in the atmosphere, which results in a slightly slower temperature increase (Fig. 12, states 2 and 3).

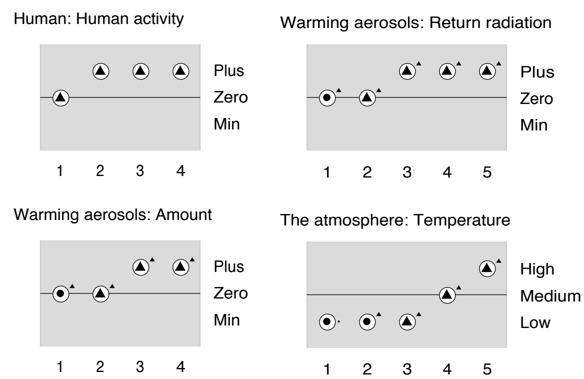

Figure 12: WA: Increasing human activity value history (Total effective radiation is not shown. It has the same values as amount of aerosols)

Low and high clouds (HLC)

High clouds are optically thin and cold, and reflect a relatively small amount of incoming solar radiation, but capture and emit the outgoing longwave radiation in the same way the two positive feedback factors we've seen so far. Therefore, their net effect on the planet is warming. Low clouds, on the other hand, being thicker and warmer, work in the opposite way, i.e. they reflect the incoming shortwave radiation back into the outer space, therefore cooling the planet. An important fact to note is that, as the temperatures rise, so do the water particles in the air. Therefore, higher temperatures would lead to more clouds in the upper layers of the atmosphere, which would in turn lead to even further increases in the temperatures, and so on. Hence, the nature of the domain gives us a unique opportunity to see both of the above presented (competing) mechanisms at work in a single, larger model.

The entity hierarchy has a similar structure as the hierarchies of the models seen so far. A new branch contains an entity called *CloudInSky*, denoting the cloud entity we will use for both of our cloud types. The most important difference is that *Effective radiation* replaces *Solar radiation* in the positive feedback mechanism, i.e. *OLR absorption* MF. The *Amount* quantity is used to represent the saturation of the sky by both cloud covers. The remaining quantities and quantity spaces are as described earlier.

The MF *Clouds* (Fig. 13) depicts the idea of the planetary temperature affecting the altitude of water particles in the global cloud cover. That is, as the temperatures rise, the amount of the low cloud cover decreases, as the water particles move to higher altitudes and accumulate in the high clouds, and vice versa.

The OLR mechanism sends back to the outer space the incoming solar radiation that reaches the surface, i.e. doesn't

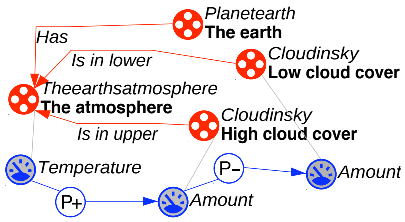

Figure 13: HLC: Clouds model fragment

get reflected by the negative feedback factors. In the two positive feedback models we've seen, we weren't taking into consideration any such factors, and the incoming solar radiation quantity was called simply *Solar radiation*. As the incoming radiation is no longer "pure", i.e. it is filtered by the low clouds before reaching the surface, the *Solar radiation* quantity in the *OLR absorption* is now represented by the *Effective radiation* quantity. The rest of the mechanism is clearly inherited from the two positive feedback models seen earlier (Fig. 14).

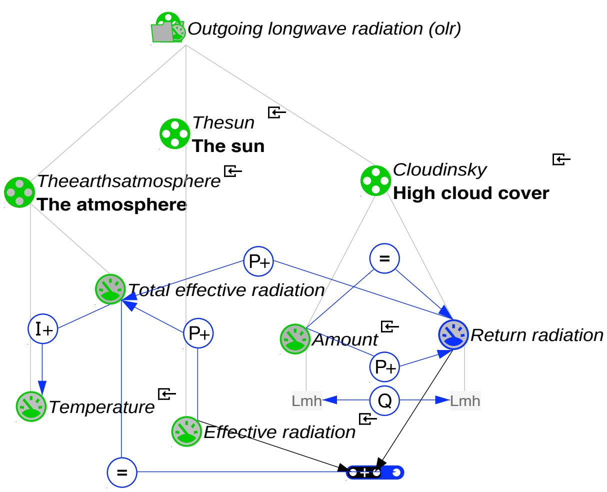

Figure 14: HLC: OLR absorption model fragment

Without assumptions the simulation produces 17 initial states and 176 states in total. Using assumptions, a particular emphasis can be highlighted. E.g. the *Decreasing solar radiation srd equals lccd* scenario proves our point, as the simulation graph is now constrained to only 3 initial states, 30 states overall, and single end-state (18), showing the main effect (Fig. 15).

Conclusion

According to the expert reviews, it appears the main goal of creating a set of simple models that would faithfully represent the domain of global warming amplifiers has been accomplished. Moreover, the secondary goal of creating a set of reusable mechanisms has also been achieved.

Most of the main deficiencies of the models have also been pointed out by the experts, as seen above. The most important issue so far appears to be the choice of quantity

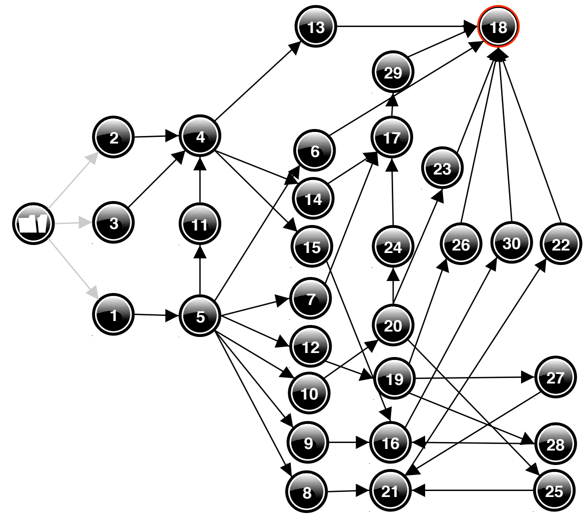

Figure 15: HLC: State graph

spaces, from the conceptual point of view, but also from the practical one, as seen in the case of the low and high cloud cover model. *Greenhouse effect* is probably a more suitable name for the external agent, than *greenhouse gases*, and the Marian Koshland Science Museum's *feedback factors* should probably carry a different name, too.

It appears that most of the other evaluators' comments revolve around personal preferences regarding the level of explicitness, or the way a mechanism is depicted. In summary, both the compliments and the criticism have been embraced, and will certainly help the models find their place in the DynaLearn project.

References

Allaby, M. 2000. *Basics of Environmental Science*. Routledge.

Bredeweg, B.; Linnebank, F.; Bouwer, A.; and Liem, J. 2009. Garp3 - workbench for qualitative modelling and simulation. *Ecological Informatics* 4(5–6):263–281.

Cioaca, E.; Linnebank, F.; Bredeweg, B.; and Salles, P. 2009. A qualitative reasoning model of algal bloom in the danube delta biosphere reserve (ddbr). *Ecological Informatics* 4(5-6):282–298.

Haupt, S. E.; Pasini, A.; and Marzban, C. 2008. *Artificial Intelligence Methods in the Environmental Sciences*. Springer Publishing Company, Incorporated.

Lerner, B. W., and Lerner, K. L. 2009. *Environmental Science: In Context*. Gale, Cengage Learning.

Philander, S. G. 2008. *Encyclopedia of Global Warming and Climate Change*. SAGE Publications, Inc.

Salles, P., and Bredeweg, B. 2006. Modelling population and community dynamics with qualitative reasoning. *Ecological Modelling* 195(1–2):114–128.

Staudt, A.; Huddleston, N.; and Kraucunas, I. 2009. *Understanding and Responding to Climate Change.* National Academies.