Creating a Model-Building Lesson on Global Warming & Potable Water Availability for a High School Environmental Science Class

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> *The ultimate test of a moral society is the kind of world it leaves its children.*
> *Dietrich Bonhoeffer*

Abstract

Educating precollege students about climate change is not a straight forward process in the best of circumstances. Unfortunately, special interest groups are working hard to spread misinformation about the causes and consequences of global warming. One possible antidote to misinformation regarding global warming is putting activities, such as building System Dynamics (SD) models, into the hands of students. It has been shown that students as young as 11 - 12 years of age can build small SD simulations and use those models to test policies. This paper contains a small global population/global temperature core model (equations provided) that students could build in free SD software. Then students could research and add one additional concept to the model that is an impact of global climate change. One example of such an additional component is the availability of easily accessible potable water. That example is also explained in this paper. The audience for this model and lesson outline are secondary school environmental science teachers who might be interested in including SD modeling in their curriculum and the members of the System Dynamics Society who might have an interest in precollege education.

Introduction

There is no question that climate change is a topic about which every adult should be well informed. Wildfires, bomb cyclones, drought, flooding and landslides, insect outbreaks, and rising sea levels are just a few of the effects we already feel. Significant current and future funding and intellectual resources are needed to address these problems. But we are currently overlooking a crucial resource in our efforts to arm ourselves for this multifaceted conflict. We are not sufficiently educating our children with the skills, tools, and intellectual strategies to face this future. One which they did not create. “In the U.S., 86 percent of teachers believe climate change should be taught in school, but nearly 60 percent of teachers report they do not teach climate change because they believe it is outside of their subject area” (Kwauk & Winthrop, 2021). Yet over 80% of U.S. parents want their children to be taught about climate change in school (Kamenetz, 2019). A UN 2021 survey found that 25% of children in the US do not consider climate change an emergency (Worth, 2021). More globally, although those countries who ratified the Paris Agreement on Climate Change agreed to support “climate empowerment,” which included educating precollege age children regarding climate change, every country failed (as of September 2021) to meet the passing level on the Climate Change Education Ambition Report Card (Kwuak, 2021).

There have been curricula designed to assist U.S. teachers in their efforts to include global climate change (GCC) lessons. A 2016 report studied nine textbooks (five in science and four in social studies) that were widely used in the U.S. and eight sets of supplemental materials that were developed by the government or not-for-profit businesses. After analysis the materials were divided into three categories: adherent (human activity plays a primary role in GCC and effects of GCC and mitigating strategies are identified), hesitant (human actions may not be responsible for GCC indicating limited effect on GCC, mentioning few mitigating strategies), and dissenting (GCC is a natural phenomenon).[1] The final analysis was that the GCC instructional materials reviewed indicated that "many U.S. high school curricula have been inadequate resources for preparing youth to understand and respond to climate change" (Meehan, Levy, & Collet-Gildard, 2018, p. 50). Replacing textbooks in schools is a very slow process. The Climate Literacy and Energy Awareness Network (CLEAN) (organized by educators with federal funding) reviewed 30,000 free educational resources about climate and found only 700 acceptable (Worth, 2021).

Moreover, there is a concerted effort in parts of the U.S. to promote misinformation about GCC. In her book, K. Worth, researched the quality of GCC education in each of the states of the U.S., supplementing the work done by several scientists who also studied the quality of GCC education by state.[2] 20 states received grades of C, D, or F, with 6 of the 20 in the F category (Worth, 2021). Unfortunately, the divide is mostly along political lines, with 19 of the 20 states with the low grades having Republican controlled legislatures (and one having a split of party control). Also unfortunately, Texas received an F, a state with an oversized influence on textbook manufacturers. "To this day, publishers shape their content around what will fly in Texas" (Worth, 2021, p87). Textbook publishers have different versions of their textbooks for different states. Worth likens the difficulty of teaching about climate change with the difficulty in the last century of schools teaching about evolution. Scientists indicate that the minimum standard about the climate change crisis that students leaving K-12 education need to have is: the "big five facts: it's real; it's us; experts agree; it's bad; there's hope" (Worth, 2021, p. 146).

So it becomes the responsibility of educators, parents, scientists, and business people who follow the fact-based science to become involved in providing leadership and materials that support teachers in their efforts to include accurate GCC information. Infusing system dynamics (SD) modeling into middle and secondary school education puts a significant amount of power in the hands of our students. Although it is possible to create SD models to support misinformation, it is much easier to reveal the assumptions that go into SD models because the models are significantly more accessible to the public (including students in middle and high school). A secondary school student who had been taught SD modeling said,

> "In other classes, I am often asked to posit logical solutions to problems or am given the solutions reached by other people. Using models of complex systems I can test out my own theories and confirm those of others instead of faithfully accepting them as fact. Where other classes ask me to memorize, this one dares me to explore." (Tommy H, age 17, student in a System Dynamics modeling high school course)

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[1] Three of the textbooks and six of the supplemental materials were categorized as adherent. Six of the textbooks but none of the supplemental materials were categorized as hesitant. No textbooks but two of the supplemental materials were categorized as dissenting.

[2] See "Making the Grade" at climategrades.org

So providing tools, that are easily accessible to precollege students, that allow them to study problems by actually building models, gives them the power to discriminate between different information being presented to them.

The rest of this paper presents a model that could be built by secondary school students, using a free SD modeling software, that relates global population change and global temperature change. It continues by giving an example of expanding the population and temperature core model by adding the concept of availability over time of easily accessible global potable water. The audience for the model and lesson outline in this paper are secondary school environmental science teachers who might be interested in including SD modeling in their curriculum and the members of the System Dynamics Society who might have an interest in precollege education.

Preliminary Considerations

If we want students in an environmental science class to build an SD model to study the topic of global climate change and the impact of easily available potable water access the model needs to be relatively small. The typical high school environmental science curriculum is packed with concepts designed to meet state and national standards so any attempt to try to introduce new instructional methodologies must not require significant instructional time. Moreover, if the new instructional methodology requires that students build models then the software required for use by the students must be easily accessible on the technology available in typical high schools (tablets, Chromebooks, or laptops). Luckily there are several free SD modeling software options that solve the latter problem, so we will focus on the former problem - designing an important lesson for an environmental science class that does not require significant instructional time. Another consideration is that any use of statical analysis of historical data must be very simple and relatively easy to accomplish with other tools that are readily available to students, like Excel. Students are expected to have background in selecting appropriate trendlines for data sets.

Before commencing with a description of a global warming & potable water model students should have had some exposure to the concept of feedback, stocks & flows, and experience with a model-building software in advance of this lesson. Discussion of feedback is naturally a part of the environmental science curriculum. The study of stocks and flows and the exposure to a model-building software can be easily accomplished by having students complete a few relatively short lessons during class and/or for homework before they undertake this global warming/potable water exercise. Previous experience building population models is highly recommended. Developing those preliminary lessons will not be discussed in this paper. (Note: this global climate change model-building lesson would be structured as a guided model-building exercise.)

Building the Model

As we begin to create a very simplified model of global climate change we would remind students that we do not model the real world but rather we model our assumptions about the real world (Gunawardena, 2014).

The model the students would build has three accumulations that each impact the other, global population, global temperature, global amount of easily available potable water. We will assume the time horizon for this model is 1950 to 2150. We will locate actual data on the Internet to give our model initial values and to provide a guide for how the model should behave from 1950 to 2020. Our concern is whether easily accessible potable water will become a problem over the next 100 years. We will start our modeling effort by building the global population segment.

Global Population Model Segment

The design of a population structure is relatively simple. The stock will be Global Population and the inflow will be global births and the outflow will be global deaths. Doing a simple exponential curve fit ($R^2 = 0.9946$) on the global population data found on the Macrotrends' website[3] indicates a net growth rate of the population of about 0.0161 from 1950 to 2020. The global population in 1950 was approximately 2.54×10^9 and the global birth fraction was approximately 0.0381. This birth fraction has been decreasing over the 70 years in question but so has the death fraction, so we will use the given birth fraction and select a normal death fraction of 0.022 to provide our net growth rate. We will assume that the birth fraction will not change during the simulation but the normal death fraction will be impacted by both increasing global temperatures and change in availability of easily accessible potable water.

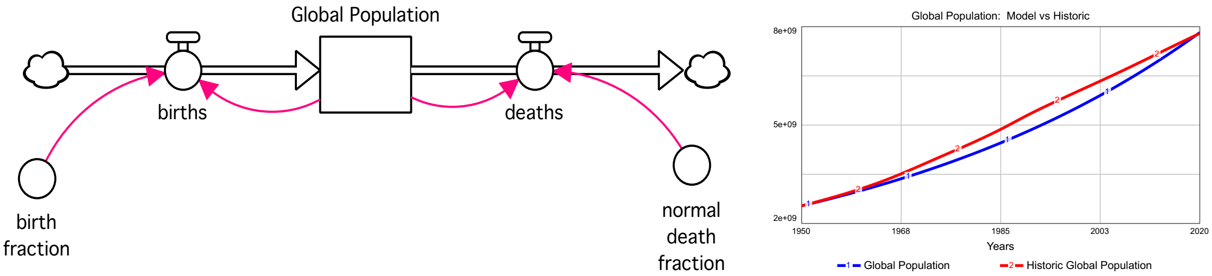

Figure 1: Global Population model segment, left. Comparison of model output for Global Population with the historical global population from 1950 - 2020.

There are techniques that could improve the fit of the population model segment to the historical population data, but as we are trying to keep this model-building lesson as simple as possible those techniques will not be used in this model segment.

Global Temperature Model Segment

The global temperature in 1950 was about 13.8° Celsius[4]. Again, doing an exponential curve fit to the data from 1950 - 2020 on the NASA website ($R^2 = 0.8893$) produced a net growth rate of global temperature of 0.0011. The starting value for global temperature in 1950 will be 13.8° C. Since population is growing exponentially and total anthropogenic influence of CO2 emission on temperature would therefore also be exponential, this growth on temperature suggests that global temperature is growing exponentially, in spite of its appearance here.

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[3] www.macrotrends.net/countries/WLD/world/population/

[4] Climate.nasa.gov/vital-signs/global-temperature/

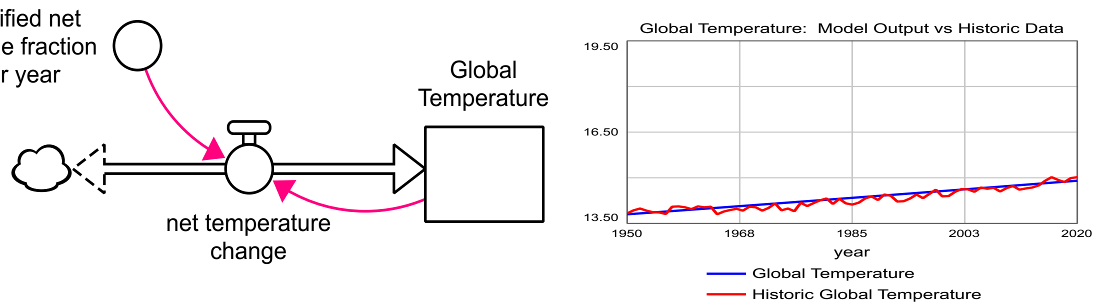

Figure 2: Global Temperature model segment, left. Comparison of model output for Global Temperature with the historical global temperature from 1950 - 2020

Combining Global Population and Temperature Segments

For the purpose of this paper the model under construction is being built in a commercial SD software. The reason is that it is helpful to see the model output regularly compared to the historical data from 1950 to 2020 to provide a measure of confidence in the initial structure of the model. To that point it is necessary to be able to display 4-5 graphs on the same grid (which is not allowed in all free SD modeling software).

At this point the Global Population structure will be connected to the Global Temperature structure.

It is expected that as the Global Temperature rises the increased temperature will have some impact on global deaths (gradually at first). To capture that concept the temperature impact on death fraction is in a slightly modified S-shaped pattern[5] starting in 1950. The impact of Global Temperature on Global Population was designed to not only conform to historical global population data[6] from 1950 to 2020 but to be reasonably close to the United Nations global population projections of 9.8 billion people in 2050 and 10.9 billion people in 2100.

Data on global fossil fuel CO_2 emissions was found on the Macrotrends website.[7] The data for emission did not follow a simple pattern of growth, showing a marked decline in 1990 that Worldwatch attributed to the "collapse of the economies of the Soviet Union and countries in Eastern Europe" that used significant amounts of coal to power their economies (Wald, 1991). Consequently two linear curve fits were applied to the per-capita calculated CO_2 emissions data, one on data from 1950 - 1989 ($R^2 = 0.8864$) and the other from 1990 - 2020 ($R^2 = 0.8072$). This information defines the component "CO2 emissions per person per year."

The impact of total CO_2 emissions on the net change fraction for Global Temperature was designed to not only conform to historical temperature data from 1950 to 2020 but to meet the

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[5] See Appendix 2 for an explanation of all dimensionless multipliers used in this model.

[6] It was necessary to raise the birth fraction by 0.001 to remain relatively close to the historic population data trend.

[7] www.macrotrends.net/countries/WLD/world/carbon-co2-emissions/

Intergovernmental Panel on Climate Change[8] (IPCC) projection of 15.5° C in 2040, and designed to continue the established trend to 2150.

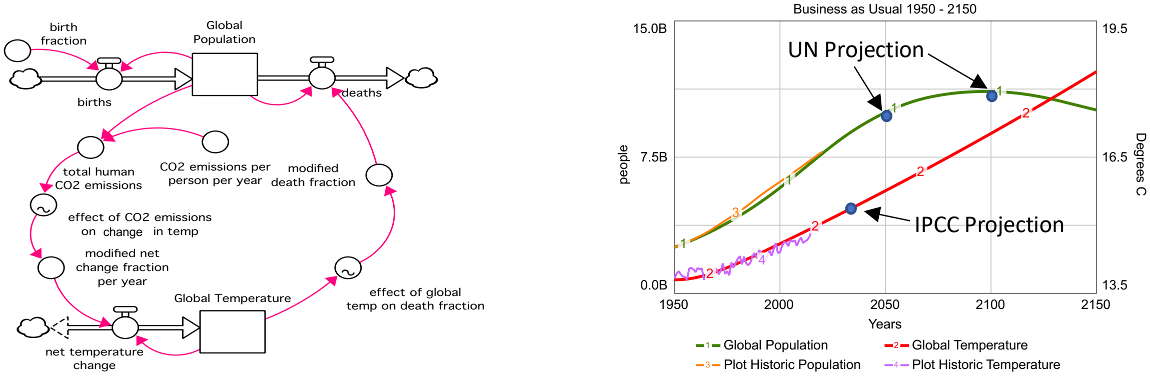
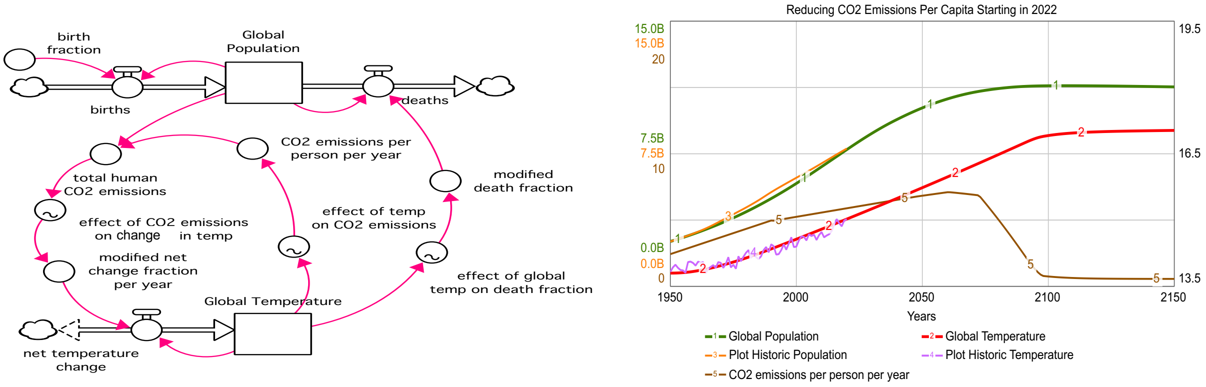


Figure 3: Mutual influence of Global Population and Global Temperature, left. Comparison of model output for Global Population and Global Temperature with the historical data represented on each graph from 1950 - 2020. Note: the model's Global Population in 2150 is projected to be 10.1 billion people.

The equations for this core model are provided in appendix 1 of this paper.

Please note that it is important not to extend the model in Figure 3 beyond the time horizon shown. If this simple model were changed to try to make it more robust to experimental changes (in the base model parameters) it would be difficult to have it track historical and projected data values. George Richardson, world renowned system dynamicist, says that "fitting a [tiny] model very carefully to data, and making it robust in the face of parameter changes, seems to work at cross purposes." Therefore, it is recommended that the model shown in Figure 3 be kept relatively intact and augmented as desired. Some examples of such augmentation are shown in the examples of Figure 4 and Figure 5.

If a plan to significantly reduce CO_2 emissions per person per year is started (gradually at first) in 2022 then revised the model segment will produce the behavior in Figure 4 on the right. The Global Temperature appears to have reached a steady-state, which is still unsatisfactory. It would be useful to determine how Global Temperature might actually decrease over time if CO_2 levels are kept very low. Will oceans eventually cool?



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[8] IPCC produces reports that are a consensus of global scientists, experts and governments on global climate change facts and issues. Its purpose is to provide scientific assessments on climate change to inform policymakers.

Figure 4: Implementing a policy to reduce CO_2 emissions starting in 2022, left. Graph of Global Population, Global Temperature, and total human CO_2 emissions (with reduction policy), right. Note: The model's Global Population projection in 2150 is 11.28 billion people.

To continue with this modeling lesson the next stage would have the core model diagram of Figure 3 displayed on paper. Then there are multiple options for augmenting this model. The teacher could break the class into groups and have each group consider additional problems that might occur with the rise in global temperature: rising sea levels, increase in potential diseases, loss of the earth's ice covering, increase in conflict due to migration of people from one country to another, impact on land available for food production, increase in air pollution, more acidic oceans, loss of biodiversity, impact on general human health to name a few. Students could pick one issue, research it, and modify the model structure adding no more than one additional stock and its accompanying flows and necessary converters to connect the new concept to the current model. Students could be given extra credit if they want to try to make their new model operational. (Caution to the teacher: Making an additional GCC concept operational will probably require the inclusion of a special graphical component where the new 3rd stock attaches to the current core model. The teacher would need to know how to create this graphical component. If the teacher is not comfortable with this procedure it is advised not to try to make the new GCC concept operational in the model.) Then student groups could present their findings, conclusions, and potential policies to the class.

If desired, the teacher could use the following discussion as an example of extending the current core model in Figure 3 to include another GCC concept: including the growing concern of long-term access to easily available global potable water. Students would not build the next segment of the model but participate in a discussion of its construction and then use a pre-built model to test potential policies.

Adding the Easily Accessible Global Potable Water Model Segment to the Core Model

The stock component to add to the core model of Figure 3 is Easily Accessible Potable Water (EAPW). The inflow would be regeneration and the outflow would be consumption. The initial amount of EAPW was calculated from the website US Bureau of Reclamations in California[9] which stated there were 326 million cubic miles of water on Earth of which 0.005 is easily available usable fresh water. That means there are $0.005 * 326 \times 10^6 = 1.63 \times 10^6$ cubic miles of easily available fresh water, which converts to 6.79×10^{15} cubic meters of EAPW in 2020. Trial and error provided a starting 1950 EAPW value of 6.94×10^{15} cubic meters of EAPW, so the model would produce the 2020 EAPW stock value. We will assume each person in our model is responsible for the equivalent consumption of water (for domestic, agricultural, and industrial consumption) to support his/her existence. The Our World in Data[10] website indicated that 1.23×10^{12} cubic meters of freshwater was used (for domestic, agricultural, and industrial use) in 1950. So, the consumption per person of freshwater (all uses) was $1.23 \times 10^{12}/2.54 \times 10^9 = 484$ cubic meters per person in 1950. The regeneration of potable water fraction was a guess (at 0.0003) developed to try to keep the regeneration inflow greater than or equal (approximately) to the water consumption outflow for the first twenty nine years starting in 1950.

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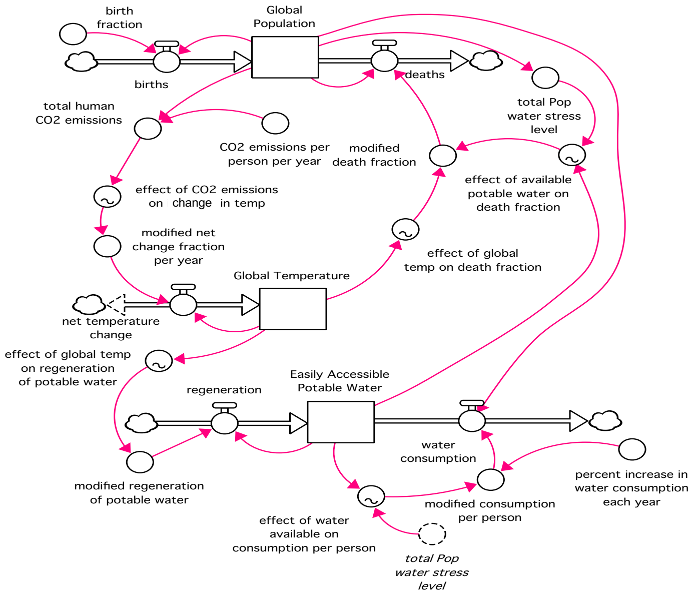
[9] https://www.usbr.gov/mp/arwec/water-facts-ww-water-sup.html

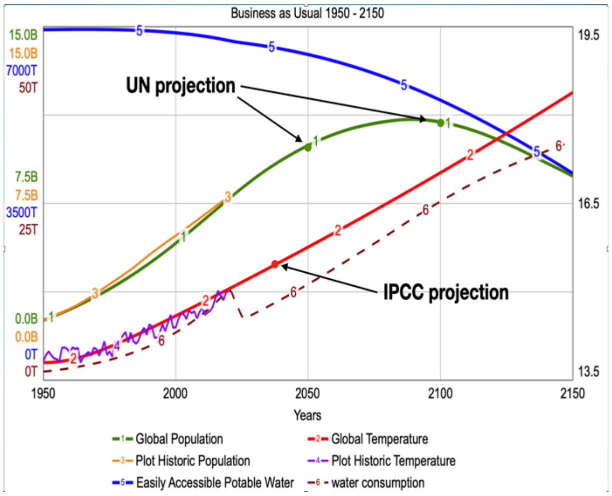
[10] https://ourworldindata.org/water-use-stress

The water stress level (the minimum amount of water, all uses, a human needs per year) is 1700 cubic meters[11] per year (Damkjaer & Taylor, 2017, Boretti & Rosa, 2019). As the EAPW level draws closer and closer to the total water stress level for the entire global population it is assumed the death fraction for the global population will increase and the amount of water allocated for consumption per person (including agriculture and industry) will be reduced.

Finally, another (perhaps more significant) problem with the long-term EAPW level is that the consumption of water, per person (including agriculture and industry), has increased by 1.8% per year for the past 100 years (Boretti & Rosa, 2019). The article does indicate that some people believe that this percentage has dropped to about 1% increase in the past decade but others do not agree that it has dropped that much. The model does reduce the percent increase in per capita water consumption over the years 2020 to 2025 to about 1%, remaining at 1% increase per year for the rest of the simulation.

Adding these considerations to the core model of Figure 3 produces the model diagram shown in Figure 5. Please note that this diagram contains 23 icons, 3 more than is allowed in the free SD modeling software Stella Online. To be able to have students execute this model a teacher would have to "bury" the information (parameter values) in 3 icons within other model icons. For example, one might want to place the birth fraction within the births inflow, the modified regeneration of potable water converter within the regeneration inflow, the modified net change fraction per year within the net temperature change biflow, possibly the modified death fraction within the deaths outflow, and if necessary the percent increase in water consumption each year in the modified consumption per person converter. This will allow the possibility of placing two additional components in the model to deal with policy considerations.





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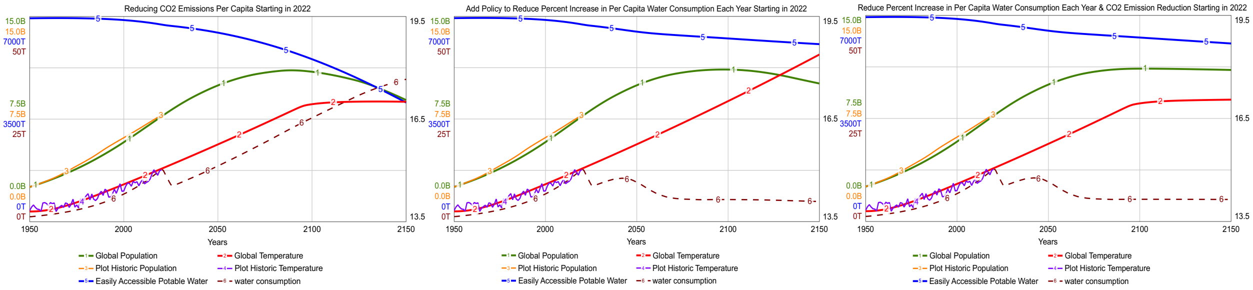
[11] Disclaimer: The first reference states the 1700 m^3 water stress level per person. The authors indicate that this value has not been empirically supported but it is used by "mainstream literature."

Figure 5: Global Population, Temperature, and Easily Accessible Potable Water Model, left. Model output for BAU Global Population, Global Temperature, Easily Accessible Potable Water, and total fresh water consumption for years 1950 - 2150. Note: the model's Global Population in 2150 is projected to be 8.7 billion.

If the teacher wants students to test some potential policies the teacher could have students test the reduction of CO_2 emissions starting in 2022 and/or reducing the percent increase in water consumption starting in 2022. Results of these policy implementations are shown in the graphs in Figure 6.



Reducing CO2 Emissions Per Capita Starting in 2022

Add Policy to Reduce Percent Increase in Per Capita Water Consumption Each Year Starting in 2022

Reduce Percent Increase in Per Capita Water Consumption Each Year & CO2 Emission Reduction Starting in 2022

Figure 6: Policies: Left: Reduce CO_2 Emissions to 23% of 1950 emissions by 2150. Center: Reduce Percent Increase Per-Capita Water Consumption to 0 by 2083. Right: Apply Both Policies. Note: Just for comparison the model's final Global Population in 2021 for Policy 1 is projected to be 8.9 billion, for Policy 2 is 10.1 billion, and for both policies is 11 billion people.

Other Important Conversations

Social Justice (just about potable water)

The method of incorporating system dynamics analysis involves more than just the science involved in building models such as those described in the previous section, but increasing the awareness of student regarding issues that are directly connected to the concepts the model highlight. One such issue that is important to consider when studying the availability of easily accessible global potable water is that not all populations will be impacted by a shortage of fresh water at the same time. As a matter of fact, 60% of the fresh water provided for the people of Saudi Arabia, today, comes from desalination plants (US-Saudi Business Council, 2021). But 1.5 liters of brine is produced for each liter of fresh water (Barrington, 2020), making it a non-sustainable solution long-term. Desalination is expensive and energy intensive, so what about the poor countries who are running out of fresh water?

Students could be broken into groups to research the state of fresh water supplies in different countries and what some countries are doing to try to meet dwindling fresh water sources. At the very least students should be aware of the impact that dwindling fresh water supplies is having on various parts of the world, currently, and what the lack of fresh water availability means to the people who are already impacted. Moreover, what is the responsibility of countries with a surplus of EAPW to people in countries that struggle to find potable water?

Student Agency (just about potable water)

As schools incorporate more technology and, hence, the ability for students to create models to supplement discussions about global issues related to rising global temperatures it is the responsibility of teachers, parents, and administrators to be aware of the potential harm that this information could have on students' emotional well-being. To present data that points to an increasingly dangerous and depressing future without presenting some elements of hope for them is irresponsible. So these lessons should also be accompanied by actions students can undertake to try to produce a more optimistic (within the realm of scientific possibility) future. Frank Niepold, a climate educator at the National Oceanic and Atmospheric Association, said currently most climate change education is 99% about the problem and only 1% about solutions. When Niepold surveyed some students about what they wanted in their education about climate change the students responded that they wanted to spend about 20% of the time learning about the problem and 80% of the time learning about solutions (Worth, 2021).

Again, students could be broken into groups to research the efforts different countries are pursuing to try to slow the decline of fresh water resources (and CO_2 emissions). Some examples for fresh water decline would be outlawing lawns, reusing wastewater, changing our consumption-based lifestyles (easy to say), reducing contamination of water supplies due to extreme weather conditions, regularly measuring and publicizing water-table levels (i.e., paying attention to bathtub dynamics), altering agricultural practices to plant fewer water-intensive food products (producing bovine meat requires a lot of water, as does nut production (Armstrong, 2021)), improving irrigation methods, building more precipitation capture devices, and considering the need to control population growth (a very explosive issue), to name a few.

But there should be some actions students could take, themselves, to move toward more water conservation, like taking shorter showers, not letting water run out of a faucet unnecessarily, talking to their parents about having the family eat less beef and drink less soda (and beer), establishing a student action group for addressing water conservation at the students' school, going to the local water department to find out which businesses in their area use the most water each month and (perhaps) working with the city council to create an award for businesses who reduce their water consumption the most over the year, etc. Students in elementary school could focus on water sustainability within their family. Middle school students could focus on water sustainability in their school. And secondary school students could look for sustainability projects within their communities.

While many of the topics mentioned in a previous paragraph are not within the purview of pre-college students, merely bringing these potential solutions to the fore is one of the reasons Jay Forrester felt that we had to infuse system dynamics analysis in pre-college education. Pre-college students will enter every part of the workforce. If they have been educated to think about these issues from a systemic perspective they will have the tools needed to find potential solutions, hopefully mitigating the most dire predictions, somewhat.

Conclusion

Misinformation about climate change is a serious (and dangerous) problem. Ninety seven percent of the scientific community has done its best to inform citizens about the anthropogenic causes of global warming. For various reasons, much having to do with companies that will be impacted financially by the reduction in the use of fossil fuels, significant groups have chosen to distort the message. This is a serious disservice to our children, who will have to live with the consequences of this enormous problem. System dynamics (SD) provides an opportunity to put power in the hands of students to draw their own conclusions from data. The simple model in this paper is an example of an effort to provide that access for students. SD modeling, with its glass box approach, has been shown to be accessible by students as young as 11 or 12 years of age. Students CAN build SD models and test policies. We should do our best to provide these powerful tools for students to build their understanding of complex problems using data from reliable scientific sources.

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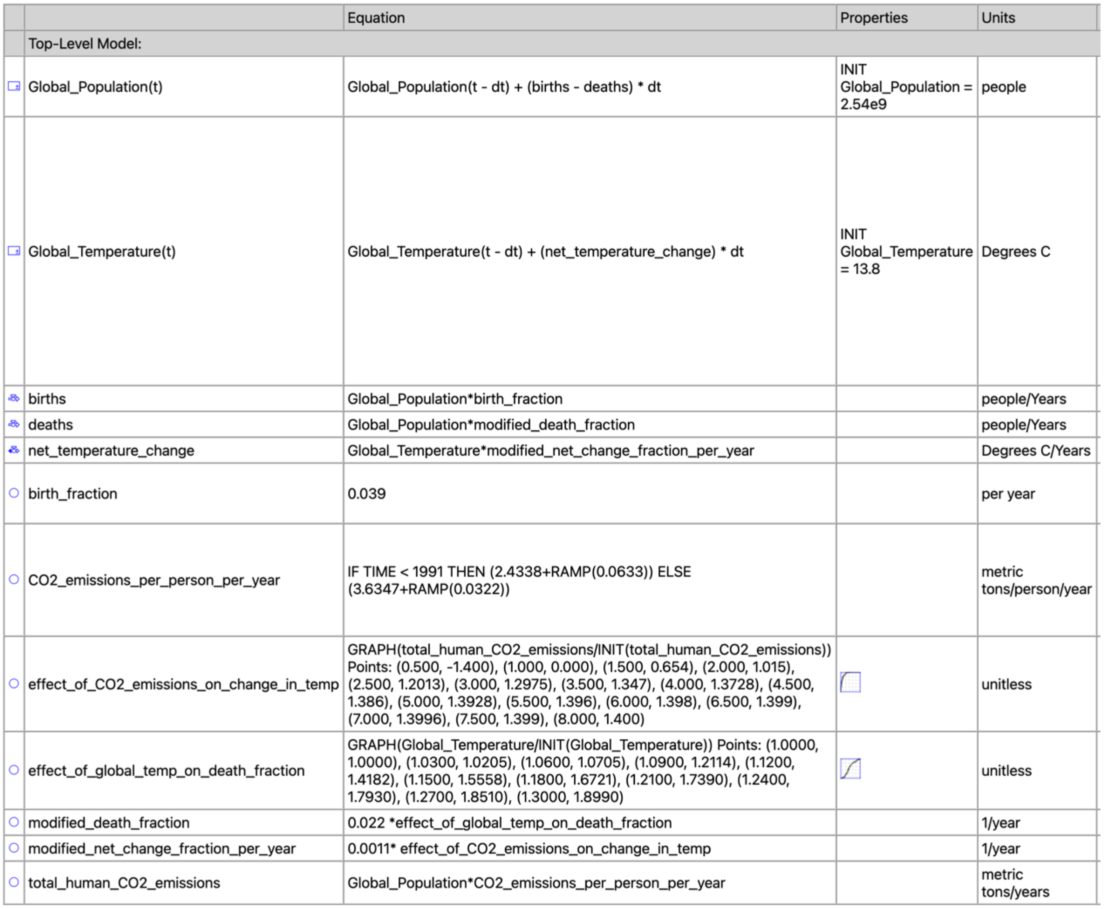
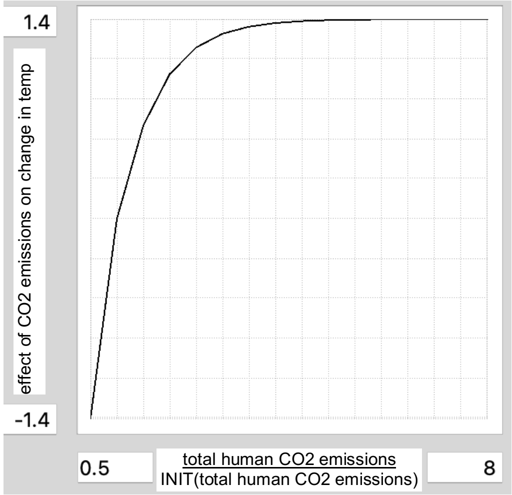
Appendix 1: The equations for the model shown in Figure 3.

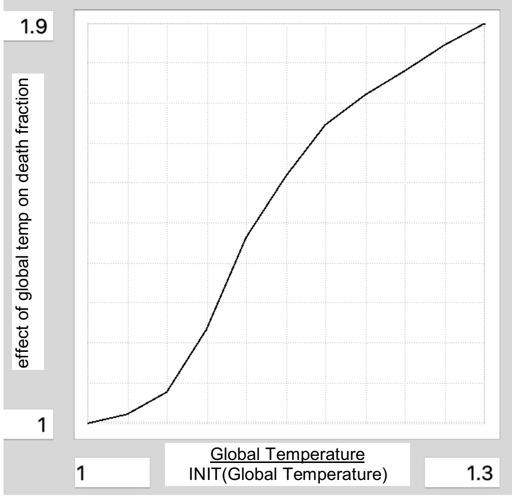


	Equation	Properties	Units
Top-Level Model:			
Global_Population(t)	Global_Population(t - dt) + (births - deaths) * dt	INIT Global_Population = 2.54e9	people
Global_Temperature(t)	Global_Temperature(t - dt) + (net_temperature_change) * dt	INIT Global_Temperature = 13.8	Degrees C
births	Global_Population*birth_fraction		people/Years
deaths	Global_Population*modified_death_fraction		people/Years
net_temperature_change	Global_Temperature*modified_net_change_fraction_per_year		Degrees C/Years
birth_fraction	0.039		per year
CO2_emissions_per_person_per_year	IF TIME < 1991 THEN (2.4338+RAMP(0.0633)) ELSE (3.6347+RAMP(0.0322))		metric tons/person/year
effect_of_CO2_emissions_on_change_in_temp	GRAPH(total_human_CO2_emissions/INIT(total_human_CO2_emissions)) Points: (0.500, -1.400), (1.000, 0.000), (1.500, 0.654), (2.000, 1.015), (2.500, 1.2013), (3.000, 1.2975), (3.500, 1.347), (4.000, 1.3728), (4.500, 1.386), (5.000, 1.3928), (5.500, 1.396), (6.000, 1.398), (6.500, 1.399), (7.000, 1.3996), (7.500, 1.399), (8.000, 1.400)		unitless
effect_of_global_temp_on_death_fraction	GRAPH(Global_Temperature/INIT(Global_Temperature)) Points: (1.0000, 1.0000), (1.0300, 1.0205), (1.0600, 1.0705), (1.0900, 1.2114), (1.1200, 1.4182), (1.1500, 1.5558), (1.1800, 1.6721), (1.2100, 1.7390), (1.2400, 1.7930), (1.2700, 1.8510), (1.3000, 1.8990)		unitless
modified_death_fraction	0.022 *effect_of_global_temp_on_death_fraction		1/year
modified_net_change_fraction_per_year	0.0011* effect_of_CO2_emissions_on_change_in_temp		1/year
total_human_CO2_emissions	Global_Population*CO2_emissions_per_person_per_year		metric tons/years

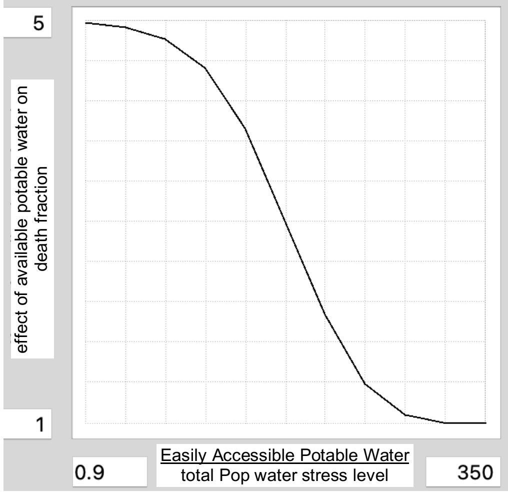
Appendix 2: Assumptions behind each dimensionless multiplier (DM)



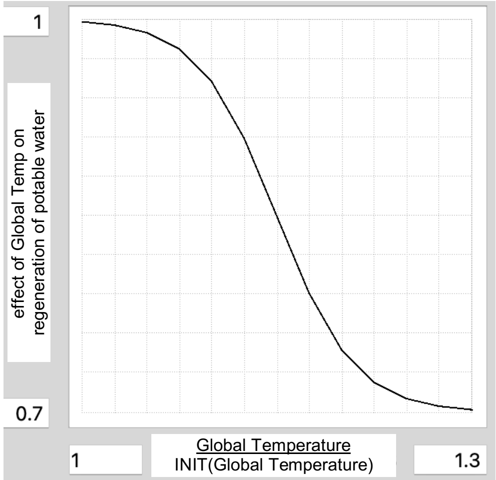
Domain ratio: The current human C02 emissions are compared to the human CO2 emissions in 1950. It is assumed the emissions will never drop below half of the 1950 emissions. The 2020 total emissions were already about 5.6 times the 1950 emission total.
Range: It is assumed that if emissions dropped below the 1950 emissions total global temperature should drop. Upper range value produced a good match for IPCC 2040 projection for temperature.
Graph: The point (1,0) is on the graph because the net change fraction for emission is using 1950 as a baseline, and the temperature change is a biflow. Total emissions above 1950 emissions increase temperature and below 1950 decrease temperature. The shape of the graph was chosen because there has been a steady increase in total emissions since 1950 and this graph produced a good match for the IPCC 2040 temperature projection. This graph may be too conservative a projection (steady state shape at the upper right) as total emissions continue to increase.



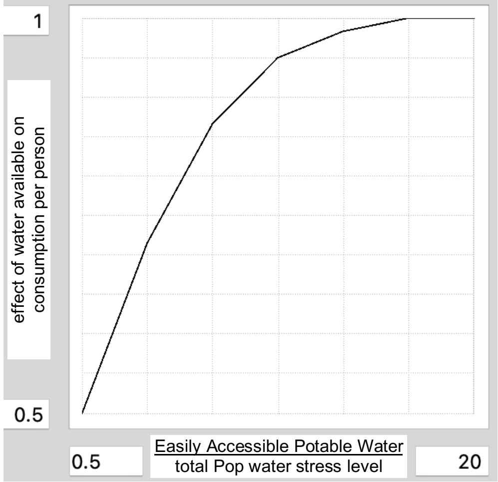
Domain ratio: The current global temperature is compared to the global temperature in 1950. It is assumed the temperature will never drop below the 1950 temperature. The 2020 global temperature was about 1.088 times the 1950 temperature.
Range: The upper range value produced a good match for the UN 2050 and 2100 projections for population.
Graph: It is assumed that the global temperature will never drop below the 1950 temperature and the global death fraction will never drop below the 1950 death fraction (due to global temperature impact). It is also assumed that the impact of temperature on population deaths would be gradual at first but always rise (as temperature rises) due to the effect of increased temperatures on severe weather events, impact on availability of food and water, impact on human health, increase in disease, increase in conflicts due to migration of people to cooler parts of the earth, etc. The shape of the graph was modified to try to match the UN 2050 and 2100 projection for population.



Domain ratio: The current (global) easily accessible potable water (EAPW) is compared to the amount of water the global population needs to meet minimum demand. The 2020 EAPW was 517 time the total population water stress level in 2020. Recall that the denominator is not a constant, but increases as the population increases.
Range: It was assumed EAPW/total population water stress level greater than 300 would not affect the global population death fraction in a significant way, but would increase the impact on the death fraction gradually at first as the EAPW/stress level continued to decrease. The upper level of the range was a guess, but guided by the UN population projections for 2050 and 2100.
Graph: It was assumed that as the EAPW amount began to move more steadily toward the total population water stress level deaths would rise significantly because water is a critical resource for human survival.



Domain ratio: The current global temperature is compared to the global temperature in 1950. The 2020 global temperature was about 1.088 times the 1950 temperature
Range: It was assumed that regeneration of potable water would not increase if temperature dropped below the 1950 temperature level and that even if the global temperature rose to 1.3 times the 1950 level (ie 17.9° C = 64.2° F) the regeneration of potable water would only fall as low as 70% of the 1950 amount. This was a guess.
Graph: It was assumed that the decline of regeneration of potable water would begin gradually as the temperature increased. The leveling off at 70% regeneration at the larger temperature range is a guess.



Domain ratio: The current (global) easily accessible potable water (EAPW) is compared to the amount of water the global population needs to meet minimum demand. When the EAPW is very close to the total population stress level this dimensionless multiplier should be activated. An upper limit ratio of 20 was chosen arbitrarily.

Range: It is assumed that if there is plenty of EAPW the normal consumption of EAPW will occur. It is assumed people are hesitant to change habits until there is a more serious lack of resource so when the EAPW becomes only 16.5 times the total population stress level water available for consumption per capita will drop quickly to 0.5 of the normal consumption amount per capita. 0.5 was a guess but a lower amount was deemed unreasonable because water is needed for human survival.

Graph: It is assumed that as the amount of potable water per capita becomes close to the total population water stress level consumption would have to be severely constrained.