An Online Climate Model to facilitate Depth-studies and Science Extension

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Simple online models of the Earth's climate are being developed by Australian universities and are increasingly being used as teaching aids in high schools. This article describes one such model developed by UNSW. "Carbonator" (www.carbonator.org) is already being used as an inquiry tool for NSW Stage 6 depth studies in Physics, Earth and Environmental Science (EES) and Investigating Science (IS).

Recent changes in the NSW Stage 6 Science Syllabus encourage inquiry-based learning through depth studies and a new Science Extension subject. Simple models can be a useful means of motivating student-led investigations, as well as educating students about the models used by scientists. The Earth's climate is ideal for students to explore with simple models. Not only are climate models a primary tool of scientists trying to understand the climate system, but these models play a key role in informing decision-making around climate change, arguably the most important environmental challenge of the day.

Climate system modelling

Greenhouse gases released into the atmosphere as a result of human activity, most importantly the release of carbon dioxide by the combustion of fossil fuels, are causing global warming and driving other rapid changes to the Earth's climate system. The primary tool for understanding how this system works and how it is likely to change in the future is the climate model (see Box 1). In the 1950s, the first climate models run on computers simulated just the circulation of the Earth's atmosphere. Today, state-of-the-art climate models have evolved to use some of the world's most powerful computers to simulate the atmosphere in much more detail, and also include components that simulate the ocean, land-surface and the ice on the Earth's surface. Given data representing a scenario for future emissions of greenhouse gases and aerosol pollutants, they can provide scenarios for the future climate of the planet. These are often communicated as maps of changes in important aspects of the climate, such as temperature. A typical simulation of this type running from the present to 2100 takes several months to run on a supercomputer.

Currently, approximately 40 research centres around the world maintain and continually develop their own state-of-the-art climate models. They provide data from the models to an international project called the Coupled Model Intercomparison Project (CMIP) (see https://www.wcrp-climate.org/wgcm-cmip). Data from CMIP can be accessed by scientists around the world and used in climate research. Results from CMIP inform many of the public statements on climate change made by the Intergovernmental Panel on Climate Change (IPCC), the United Nations body charged with providing policymakers with regular assessments on what we know about climate change. These statements can be influential in determining government policies on climate change and in international negotiations on how to combat it.

'Carbonator': A simple climate model

'Carbonator' is a simple climate model that runs online in seconds (see Box 2). It is much less detailed than a state-of-the-art climate model, and does not produce maps of changes in the climate. However, it uses many of the same principles to simulate changes in global average temperature in response to imbalances between the amount of energy that the Earth receives from the Sun and the energy that it radiates into space. These imbalances arise from climate ***"forcings"*** due to emissions of greenhouse gases and aerosol pollutants into the atmosphere by human activity, emissions of aerosols into the atmosphere by volcanoes, variations in the energy received from the Sun and changes in the reflectivity of the Earth's surface. As with a state-of-the-art climate model, carbonator must be provided with data related to these *forcings* (e.g. a time series of annual human emissions of carbon dioxide into the atmosphere for the years 1850 to 2100).

The effects of climate change are often summarised in terms of changes in the global average temperature of the Earth's surface. As well as outputting these data, 'carbonator' also outputs other data that help students understand the effects of greenhouse gas emissions, including how additional carbon released into the climate system is partitioned between the atmosphere, vegetation, soil, the ocean and the size of the climate forcing resulting from the atmospheric component. Other topical data outputted by the model include changes in the sea level and the acidity of the ocean.

An Online Climate Model to facilitate Depth-studies and Science Extension (continued)

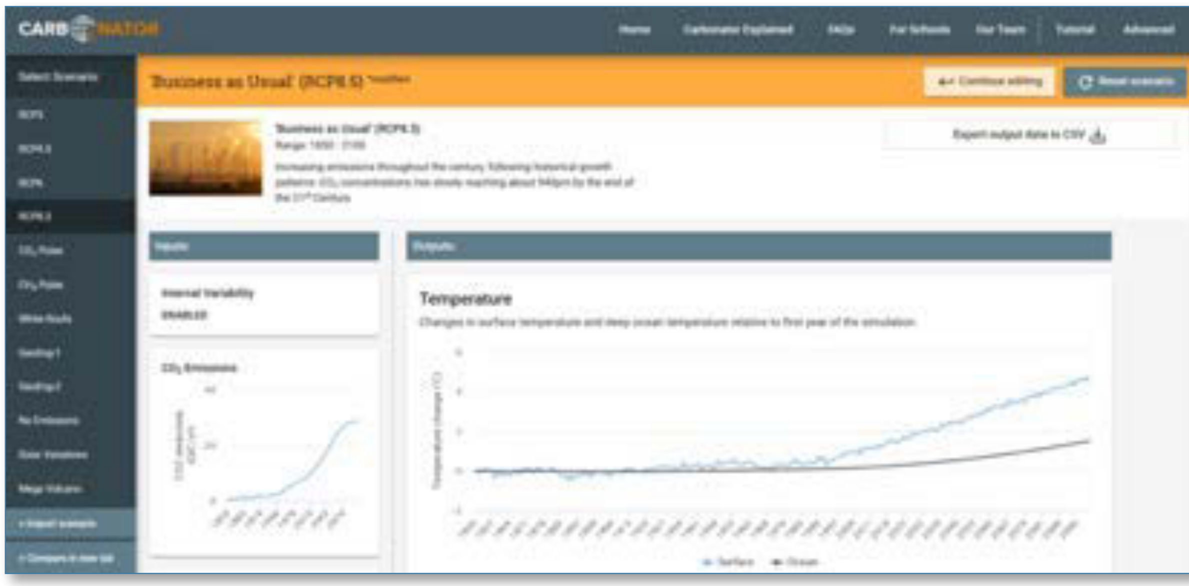

Figure 1. Example 'carbonator' simulation (Image attribution: CCRC, UNSW Sydney (NonCommercial-ShareAlike (CC BY-NC-SA 2.0 AU)))

Figure 1 shows some of the inputs and outputs of an example 'carbonator' simulation, as shown by the 'carbonator' web interface. It simulates the effects of an internationally-recognised scenario ("RCP8.5") under which annual global emissions of carbon dioxide from human activity continue to increase throughout the 21st century (on what is often called a "Business as Usual" trajectory). The simulation runs from 1850 to 2100. The output of the model shows that the forcing produces a steady increase in the global average surface temperature right to the end of the 21st century (blue line). The output also shows the effect of variations in the energy imbalance of the climate system due to "internal variability" caused by natural phenomena such as El Niño. This results in year-to-year variations in the temperature on top of the overall warming trend. Hence one year can be cooler than the preceding year even if the climate is warming due to human greenhouse gas emissions. Below the surface, the temperature of the deep ocean warms much more slowly and is not significantly affected by the internal variability simulated by the model (black line).

Carbonator's online interface allows students to immediately run a range of such pre-set internationally-recognised scenarios for future emissions of greenhouse gases, additional scenarios thatallow students to explore some of the ideas that have been proposed to reduce climate change, and more theoretical scenarios designed to examine the effects of sudden increases in atmospheric greenhouse gas concentrations.

Using 'carbonator' in high schools

The 'carbonator' web interface (www.'carbonator'.org) is designed to allow for hypothesis testing and exploratory investigations with sufficient flexibility to allow teachers to scaffold the analysis or utilise a differentiated approach for students with varied interest or abilities. The interface allows students to explore beyond the pre-set scenarios provided, by manipulating inputs, redesigning existing climate-forcing scenarios (simply by manipulating input data) or creating completely new scenarios (using .csv spreadsheets). The outputs can also be downloaded into spreadsheets so that students can perform a range of statistical analyses comparing various scenarios.

Two depth study examples using 'carbonator' are provided on UNSW's Open Learning Platform (https://openlearning.com/unswscience) covering the Greenhouse Effect for EES and climate models for IS. The depth studies are free to teachers and include foundational knowledge on each topic as well as an editable worksheet that can be assigned to students as a familiarisation exercise. Teachers may wish to use the foundational knowledge to brush up on their own knowledge on the topic, or use for class to fill gaps in their textbook resources.

The 'carbonator' worksheet or the ready-made experiments can be used in class, and students can then be assigned tasks such as testing specific hypotheses.

UNSW is a partner in the ARC Centre of Excellence for Climate Extremes, a 7-year research collaboration between UNSW, Monash University, the University of Melbourne, the Australian National University and the University of Tasmania.

Both UNSW and the Centre of Excellence are working to better equip science teachers to teach climate science. The authors welcome feedback on 'carbonator' and discussions on other climate science teaching resources – they can be contacted via a.maharaj@unsw.edu.au.

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Box 1 – How do climate models work?

State-of-the-art climate models are complex constructions in which the climate system is divided into a three-dimensional array of grid cells – Figure 2 shows this for the atmosphere component of a model. As a model simulation steps forward in time, relevant properties of each cell (e.g. air temperature, wind humidity for an atmospheric cell, water temperature, currents and salinity for an ocean cell) are modified according to mathematical equations representing physical and biogeochemical processes. These equations govern how properties in a cell are affected by neighbouring cells (e.g. by currents transporting heat around the ocean) or are modified within the cell (e.g. by the formation of clouds). The equations enshrine fundamental laws, such as the conservation of mass, energy and momentum, in the model.

These workhorses of climate science typically require hundreds of person-years to develop, are made up of millions of lines of computer code and are run on tens to thousands of processors on large supercomputers. The complexity of the models means that their outputs can be almost as difficult to analyse and understand as observations of the real world.

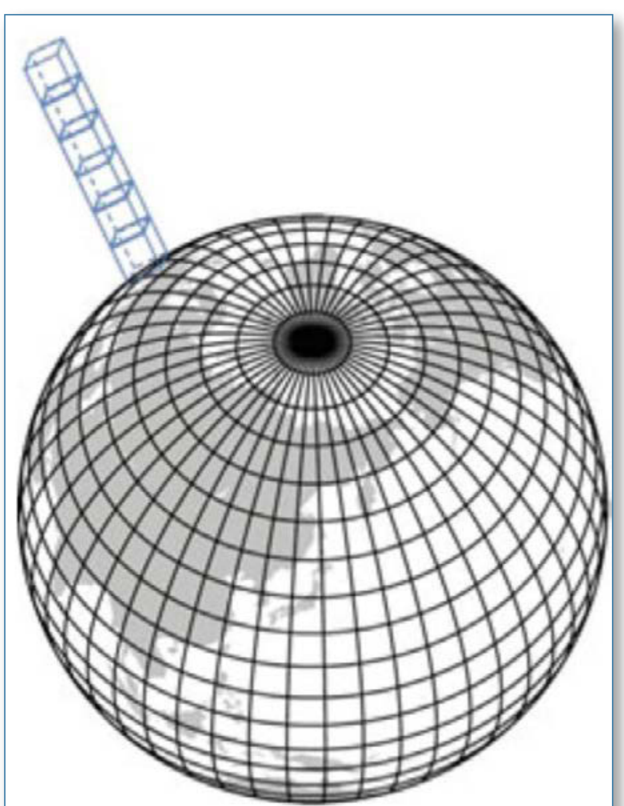

Figure 2 Schematic of the three-dimensional grid of the atmosphere of a climate model (Image attribution: CCRC, UNSW Sydney (NonCommercial-ShareAlike (CC BY-NC-SA 2.0 AU)))

Box 2 – How does carbonator work?

At the heart of a state-of-the-art climate model lies the principle of the conservation of energy. Any imbalance between the energy entering and leaving the climate system will cause the temperature to change (until an equilibrium is reached). Regional imbalances in the build-up of energy require the redistribution of heat through the climate system (i.e. between grid boxes) via the simulated movement of air and water. However, to understand the first order response of the climate system to energy imbalances – i.e., the globally averaged response – we can do away with the array of grid cells needed to resolve regional changes. Instead we can treat the climate system as a homogenous body – such as a box - that warms or cools via energy imbalances. Carbonator treats the climate as two interconnected boxes that respond to energy imbalances on different timescales. The "surface climate" includes the lower atmosphere, the land surface and the well-mixed surface ocean (~ top 50m). These regions interact rapidly and so can be represented by a single temperature. The surface temperature responds rapidly to changes in energy input as it has a relatively small heat capacity.

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1. The "deep ocean", which has a large heat capacity and responds much more slowly to energy input.

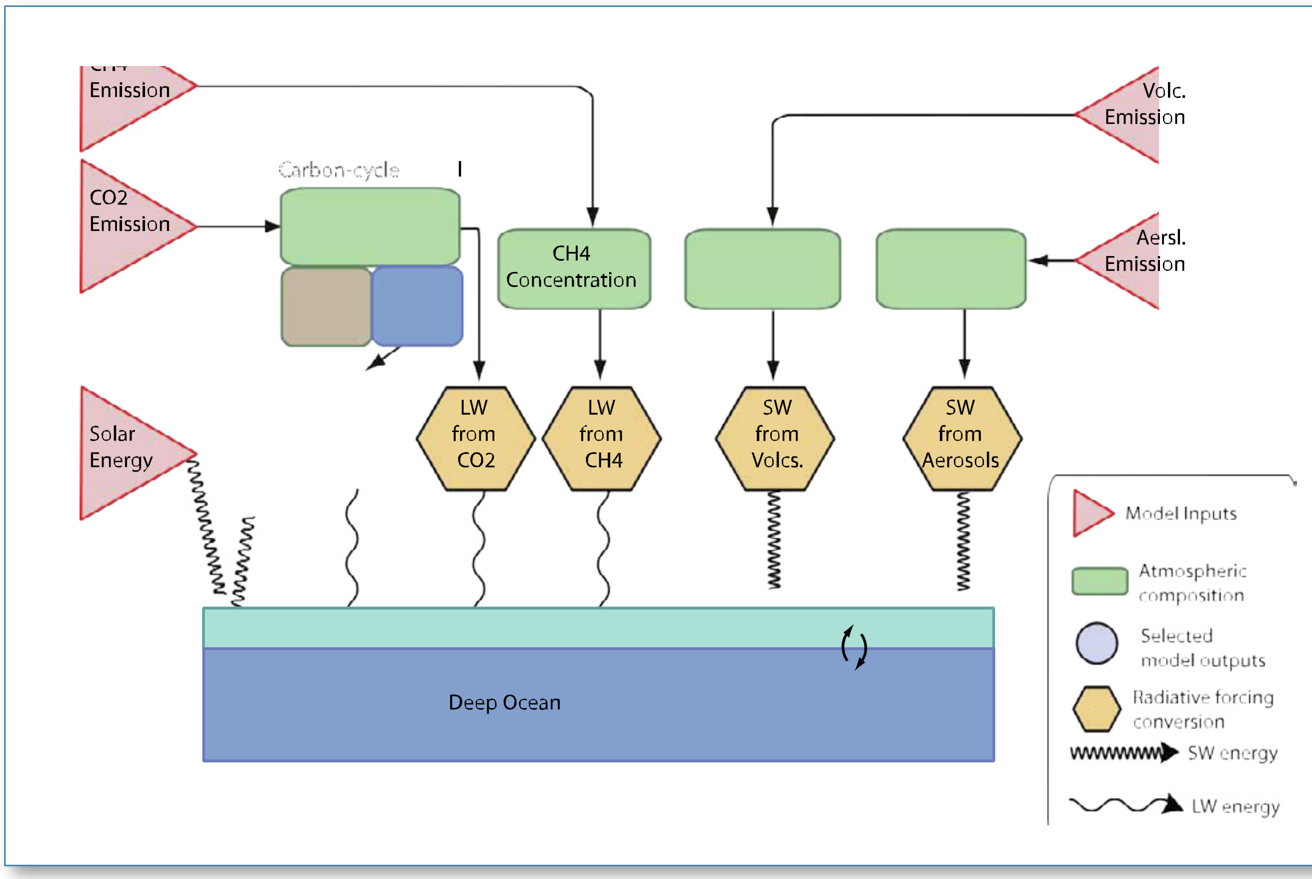

Figure 3 Schematic of 'carbonator' (Image attribution: CCRC, UNSW Sydney (NonCommercial - ShareAlike (CC BY-NC-SA 2.0 AU)))

Additional energy reaching the surface is quickly redistributed through the upper ocean, lower atmosphere and land surface, causing them to warm rapidly. Heat very gradually mixes from the upper ocean to the deep ocean. However, the deep ocean has a very large heat capacity, so temperatures change more slowly, on centennial timescales. Given input information about changes in energy entering and leaving the surface climate over time, the 2-box energy balance model calculates globally-averaged surface and deep ocean temperature anomalies[1], depicted as T_{surf} and T_{deep} in Figure 3.

To determine how much energy is entering and leaving, the 2-box model is coupled to component models related to the emission of greenhouse gases (only the two primary greenhouse gases emitted by human activity, carbon dioxide and methane, are considered), volcanic and human (sulfur dioxide) aerosol emissions and incoming energy from the Sun. Model inputs are depicted in triangular form in Figure 3. The component models also provide additional outputs, including atmospheric concentrations of carbon dioxide, methane, volcanic and human aerosols (green rectangles figure 3), carbon stored on the land (brown rectangle) and in the ocean (blue rectangle) and ocean acidity (depicted by pH in the figure). Each of these component models calculates changes in incoming shortwave (SW) or longwave (LW) radiation.

Additional inputs include solar radiation that is reflected back out to space without interacting with the climate system (albedo) and feedback processes that serve to amplify or suppress changes in the surface climate temperature and hence, longwave energy out. A further component model (not included in the schematic) estimates sea level from the ocean temperature information.

[1] A temperature anomaly is the change in temperature since pre-industrial times (when the climate system is assumed to be in equilibrium, i.e. temperatures were steady)

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More detail on the model and its various components is provided on the carbonator website (see http://144.6.234.149:8080/explained).

Box 3 – Stage 6 syllabus outcomes relevant to carbonator

Earth and Environmental Science

Syllabus outcomes

Develops and evaluates questions and hypotheses for scientific investigation EES11/12-1

Communicates scientific understanding using suitable language and terminology for a specific audience or purpose EES11/12-7

Conduct investigations to collect valid and reliable primary and secondary data and information EES11/12-3

Solves scientific problems using primary and secondary data, critical thinking skills and scientific processes EES11/12-6

Analyses the natural processes and human influences on the Earth, including the scientific evidence for changes in climate EES12-14

Content

Module 3: Energy Transformations (Role of Energy in Earth's processes; Transformations in the Oceans, Biosphere and Cryosphere)

Module 7: Climate Science

Investigating Science

Syllabus outcomes

Design and evaluate investigations in order to obtain primary and secondary data and information INS11/12-2.

Conduct investigations to collect valid and reliable primary and secondary data and information INS11/12-3.

Develops and engages with modelling as an aid in predicting and simplifying scientific objects and processes INS11-0.

Content

Module 3: Scientific Models

Physics

Syllabus outcomes

Conducts investigations to collect valid and reliable primary and secondary data and information PH11/12-3

Selects and processes appropriate qualitative and quantitative data and information using a range of appropriate media PH11/12-4

Solves scientific problems using primary and secondary data, critical thinking skills and scientific processes PH11/12-6

Communicate scientific understanding using suitable language and terminology for a specific audience or purpose PH11/12-7

Explains and analyses waves and the transfer of energy by sound and light PH11-10

Content

Module 3: Waves and Thermodynamics (Thermodynamics)

Science Extension

Syllabus Outcomes

Uses statistical applications, mathematical processes and/or modelling to gather, process, analyse and represent reliable and valid datasets SE4

Analyses and reports on a contemporary issue or an application of science informed by primary or secondary-sourced data, or both, in relation to relevant publicly available data sets SE6

Content

Module 3: The Data, Evidence and Decisions°