Imagine being able to take a planet and select its characteristics: distance from the sun, tilt of the axis of rotation, rotation rate, greenhouse gas concentrations, location of continents and mountains, etc. Imagine selecting these characteristics from a web page and pushing the “go” button. A climate model runs and produces the climate on that world nearly instantaneously, returning the results to view and analyze. The results would engage users in understanding the controls on Earth’s climate. Sounds fun, huh?

This was our original vision: to create this dynamic, live interface for users and to take advantage of the creativity of a large user base to pursue scientific questions about Earth’s climate system. Unfortunately, realizing such a vision is not currently possible with the speed of today’s computers. Even using a simplified and coarse-resolution climate model built for speed, our supercomputer will produce only about 480 years of model climate in one day. Because 50–300 years of simulations are needed to obtain a stable climate and with potentially many users submitting simulations in real time, our supercomputer would be quickly overwhelmed. Even producing the full suite of model graphical output takes on the order of an hour for a single processor. Instead, we scaled back on this vision. We preselected about 50 Earths, performed the computer simulations ourselves, and created visualizations of the output, all ready for the users.

The result was Build Your Own Earth (www.buildyourownearth.com). Now, this web-based tool is made freely available to other instructors, students, and researchers to explore the climates of the past, present, and future Earths, along with some idealized Earths. Build Your Own Earth is a cousin to Monash University’s Simple Climate Model (http://monash.edu/research/simple-climate-model/mscm), which offers over 1,000 different simulations. Whereas the Monash Simple Climate Model is a globally resolved energy-balance model (Dommengen and Flöter 2011), Build Your Own Earth is a coupled atmosphere–ocean–sea ice general circulation model. In this article, we describe the model at the heart of Build Your Own Earth, the initial 50 simulations, and how we have employed it in teaching and research.
MODEL FORMULATION. The climate model is the Fast Ocean Atmosphere Model (FOAM; Jacob et al. 2001), a general circulation model optimized for efficient and fast simulations. FOAM couples three different models, with two-way interactions between the atmosphere and ocean general circulation models, as well as an interactive sea ice model. The atmosphere model is based upon the National Center for Atmospheric Research Community Climate Model, version 2 (NCAR CCM2; Hack et al. 1993). The ocean model component of FOAM is OM3, which is similar to the Geophysical Fluid Dynamics Laboratory (GFDL) Modular Ocean Model, and the land surface and sea ice models are based upon those found in the Parallel CCM2 (Jacob et al. 2001). To keep the model simple and fast running, some feedbacks are not included. For example, topography, bathymetry, vegetation, atmospheric chemistry, and land surface type are fixed within each simulation. Although ice sheets will grow, they do not become kilometers deep and become part of the terrain. The absence of these feedbacks potentially limits the model’s ability to simulate the climate accurately in some scenarios. Despite its simplicity, FOAM has been used in dozens of research publications on paleoclimate, snowball Earth, vegetation feedbacks, and atmospheric teleconnections (www.mcs.anl.gov/research/projects/foam/publications.html).

For simplicity and owing to the uncertainty in the paleobathymetry, the continental shelves were set to 110 m and the deep ocean was set to 3,100 m. The paleovegetation was assumed to be a function of latitude (Matthews 1983), which is the default assigned by the model boundary condition generator Slarti. Because past paleoclimate experiments using FOAM have typically used one fixed vegetation classification (e.g., Donnadieu et al. 2006; Zhang et al. 2011), our simulations potentially provide more realistic vegetation in the absence of a fully coupled vegetation model.

The horizontal grid spacing in the atmosphere is 4.5° × 7.5° latitude–longitude (about 500 km × 800 km near the equator) with 18 levels, and the horizontal grid spacing in the ocean and sea ice models was 1.4° × 2.8° latitude–longitude with 24 levels. The time steps in the atmosphere and ocean/sea ice models were 20 and 240 min, respectively. This coarse grid spacing means that there will be features in the real world that will be underrepresented or poorly simulated in the climate model, such as the stationary Rossby waves forced by mountains.

As of December 2016, 50 different simulations are hosted on Build Your Own Earth. These simulations are time-slice simulations, meaning that the model was run out for a number of years in order for each simulation to reach equilibrium, as defined by the stabilization of the global-mean annual-mean temperature over time. This spinup time usually was 50–300 years. Then, the last 30 years of simulation were analyzed as the climate. Fifty different quantities can be viewed for each simulation in Build Your Own Earth, such as the mean monthly surface temperature and precipitation, cloud fraction, winds (surface, 850, 500, and 250 hPa), net solar radiation at the surface and the top of the atmosphere, top-of-atmosphere solar insolation, sea ice fraction and thickness, ocean currents and salinity, and land surface albedo. The three categories of simulations—Recent, Ancient, and Alien Earths—are described below.

Recent Earths. The Recent Earth simulations all use the current continental configuration. The default simulation is called the Current Day (2015) simulation with 400-ppm carbon dioxide; 326-ppb N₂O; 1,750-ppb methane; 236-ppt CFC-11; and 527-ppt CFC-12. Other simulations designed to test the sensitivity of the climate to greenhouse-gas concentrations include a preindustrial control simulation (280-ppm carbon dioxide, 306-ppb N₂O, 700-ppb methane, and no CFCs), a simulation from 1975 (335-ppm carbon dioxide; 275-ppb N₂O; 1,500-ppb methane; 130-ppt CFC-11; and 300-ppt CFC-12), a simulation with no greenhouse gases, and a series of simulations that vary just the carbon dioxide concentration including twice the preindustrial scenario and the Intergovernmental Panel on Climate Change (IPCC) A1F1 scenario for 2100 with 1,000-ppm carbon dioxide]. Other simulations vary the solar constant, axial tilt, and eccentricity. A final set of simulations varies only the orbital parameters through the most recent glacial cycle (0; 3,000; 6,000; 8,000; 11,000; 21,000; and 126,000 years ago).

Ancient Earths. Ancient Earths include snapshots from the geologic past, such as the Last Glacial Maximum, Miocene, Jurassic, Triassic, Carboniferous, Cambrian, and Ediacaran. Two simulations were performed at the Cretaceous–Tertiary boundary—one before and one after a hypothetical asteroid impact that increases the aerosol optical depth of the atmosphere by a factor of 3. The solar constant in all Ancient Earth simulations was set at the present-day value of 1,367 W m⁻², and the rotation rate of Earth was its present value of 7.292 × 10⁻³ s⁻¹, even though these characteristics were likely different further back in time. Paleogeography reconstructions from Colorado Plateau Geosystems (Blakely 2014; https://deeptimemaps.com/) along with atmospheric composition reconstructions from Royer et al. (2004) were used. Although reconstructions for
carbon dioxide have been created (e.g., Ward 2006, p. 30), reconstructions of methane do not exist. Thus, a ratio of $2.5 \times 10^{-3}$ methane to carbon dioxide concentrations in the atmosphere was used; this ratio is the same as the value during the preindustrial simulation and appears reasonable in the absence of any other information about the paleomethane concentrations. Because the atmospheric carbon dioxide and methane concentrations millions of years ago are not well constrained, some caution should be applied when viewing these simulations. In the absence of more rigorous verification, they should not necessarily be viewed as factually accurate representations of past environments, but as a best estimate of what changing ocean and land configurations and atmospheric composition can do to the climate.

To test the sensitivity of the paleoclimate to concentrations of greenhouse gases, we employed a small test. For the Jurassic simulation, Gugliotta et al. (2016) performed simulations with low and high concentrations: carbon dioxide and methane concentrations at 1,080 and 2.7 ppm, respectively, versus 3,000 and 7.5 ppm, respectively. Despite the global-mean temperature being nearly 5°C higher for the high-concentration simulation, the simulations did not yield a qualitatively different precipitation or temperature pattern, suggesting that the patterns of climate regions may be relatively insensitive to changes in greenhouse gas concentrations in such models, at least in some scenarios.

**Alien Earths.** The Alien Earths category considers idealized Earth configurations. What is the effect of no continents on Earth (i.e., aquaplanet) or no oceans (i.e., terraplanet)? What would the circulation look like during a snowball Earth episode (i.e., iceplanet, which would be like the planet Hoth from *The Empire Strikes Back*)? What would happen if a single continent existed on the equator? Or on the pole? What if the whole Earth was land except for a single ocean in the middle? These simulations help students bridge the gap between thought experiments about Earth’s climate in their textbooks (e.g., sections 10.1 and 10.2 of van Andel 1994; chapter 6 of Ruddiman 2008) and fully prognostic and dynamically consistent model simulations.

![Fig. 1. Earth and climate property selection screen for Build Your Own Earth.](image-url)
THE INTERFACE. The website was designed with three principles: a simple user interface to facilitate access to the broadest possible user group typical of an online course, scientifically accurate model output, and an attractive design. The user first enters the website and encounters a screen that offers two selections: the specific Earth simulation and the climate property to view (Fig. 1). A schematic of Earth rotating is displayed, along with the orbital characteristics and gaseous atmospheric composition.

When the “view model” button is pressed, the screen changes to an animation of the annual cycle of the selected property (Fig. 2). The user can start and stop the animation and control its speed. Two sliding bars (one left–right and one up–down) allow the user to compare the same property for two simulations during the animation. The output can be viewed in one of four possible map projections: cylindrical equidistant centered at the prime meridian or the international date line, north polar stereographic, or south polar stereographic.

The website has been designed with students and first-time users in mind. First, the website works across devices, from different mobile phones to desktop screens, which helps encourage broad usage. Second, a self-guided tour walks the user through the various components and functionalities of the website, and four YouTube video tutorials provide even more guidance about how to use and interpret the website and its model output. Third, with a single click, students can download images *dynamically* created on their screen (as perhaps from two different simulation views), thus allowing them to include images of any model comparison in reports or assignments.

TEACHING. The funding and motivation for Build Your Own Earth came from the University of Manchester’s funding for the development of massive open online courses (MOOCs) on the Coursera website (Coursera.org). We proposed and received funding for the development of a MOOC entitled “Our Earth: Its Climate, History, and Processes” (www.coursera.org/course/ourearth). MOOCs are free online courses that can be taken by anyone who registers. Thus, MOOCs are often a mix of traditional students looking to expand their knowledge or to see a different perspective on their material, more mature learners who may be taking the course as informal
continuing professional development, or retired individuals just simply interested in learning.

Build Your Own Earth was released to students in the first cohort of the MOOC that started in January 2015. An optional assignment was created with multiple-choice questions that walked students through the tool and some of the simulations. The questions were aimed at getting the students to appreciate three things.

1) Despite the large number of configurations of Earth presented in Build Your Own Earth, the simulations produce some basic characteristics of the general circulation, such as the intertropical convergence zone, dry subtropics, and mid-latitude jet streams. Although the details of these features may change from simulation to simulation, their consistency tells us something about the stability of the planetary-scale circulation.

2) The global-average temperature is a relatively simple metric that fails to illustrate the wonderfully rich patterns associated with the planetary-scale circulation and the annual cycle. These simulations might cause some to reconsider the claim that certain geological periods are “hot” or “dry” in geological time. This lesson provides an interesting thought exercise for geology students who might be tempted to overgeneralize the results of their single field site.

3) It is these rich patterns that control the local climate of temperature, precipitation, and wind, which then determine the various ecosystems for plant and animal life, as well as sedimentary environments.

In response to feedback from the students, for the second and third cohorts (which started in June 2015 and January 2016, respectively), we recorded the four short videos that provided more guidance for students on using Build Your Own Earth and interpreting the climate model output. The assignment was also revised and made mandatory.

End-of-the-MOOC evaluations were compiled from these two cohorts, with the overwhelming majority of the students finding the tool useful to their understanding (Fig. 3). One student said, “This is the first time in over 50 years that I’ve even looked at Earth Science. I’m literally ‘blown away’ by the power of the simulation for gaining an understanding of how the Earth works now and in the past. I’m hooked!”

In September 2015, EART10111 Planet Earth at the University of Manchester ran, which is a required course for all first-year geoscience majors. The Build Your Own Earth assignment was improved, some multiple-choice questions were expanded to short-answer questions, and two essay questions were added at the end. The first essay question asked for comments to improve the Build Your Own Earth (BYOE) interface. The second essay question was the following:

Pick a scientific question that you could answer with simulations that are not currently in BYOE. Design a simulation or series of simulations that you would like to perform. Hypothesize what results that you might expect. Explain the simulation and the hypothesized results. Explain your answer.

Although some students did not engage with this question or missed the point, a few provided elaborate answers that included graphics from peer-reviewed paleoclimate articles to explain what they might expect. One comment by a student from the end-of-the-semester evaluation provided the following thoughts about the assignment:

The BYOE assignment made you think for yourself and explain your reasoning, showing innovation and meaning the answers were not just on the internet… This was a very good assignment because it made people think for themselves and make their own hypotheses and assumptions. Plus, the last question is really what I want to be asked at University. I want to write innovatively and not just the right answer in a textbook.
At the end of the semester, students were asked about whether they learned from the assignment and whether they felt the assignment was a good use of their time (Figs. 4 and 5, respectively). In 2015, only slightly more students had favorable opinions about the assignment than unfavorable opinions. In 2016, we redesigned the assignment almost entirely from scratch, favoring an approach with learning embedded into the assignment, eliminating almost all multiple-choice questions and replacing them with questions testing higher-level thinking skills and library work, and adding content of more relevance to their learning in future years. The assignment grew in length, too (perhaps a bit too much, as some students commented that the assignment was too long for the 8–10 h we suggested). These changes improved the student perceptions of the assignment. In 2015, 25% and 26% of students had a negative view of the assignment as recorded by the two questions; in 2016, these numbers dropped to 7% and 13% respectively (Figs. 4 and 5).

In addition to the MOOC and the classroom, Build Your Own Earth has been used for undergraduate dissertation research, public engagement, and undergraduate recruitment. It has truly become a multipurpose educational tool.

**RESEARCH.** Build Your Own Earth has also been used to develop interdisciplinary research collaborations. Several examples follow. First, we were able to help demonstrate that cycles in sedimentary deposition in a field site in Argentina deposited on a river delta in Gondwana 170 million years ago were caused by the seasonal shifts of the general circulation. We used the Jurassic simulation to show the strong seasonal pattern in the paleolocation where average monthly precipitation ranged from 4 mm in the dry season to 34 mm in the wet season (Gugliotta et al. 2016). The output from the model was consistent with the interpretation from the sedimentary record of alternating river-flood and interflood periods.

Second, the simulation with Earth’s axis tilted at 90° follows the work of a recent publication that studied the role of ocean dynamics on an aquaplanet at high obliquity (Ferreira et al. 2014). Our simulation takes that work to the next step with continents on the planet.

Third, because we have a consistent set of simulations through geological time, we have the ability to do controlled experiments on this set. Specifically, we have performed a set of simulations holding carbon dioxide fixed and varying only the continental configuration. In this way, we can quantify the relative importance of continental configuration versus atmospheric composition to changes in climate over geological time, similar to the approach of Lunt et al. (2016).

Finally, Build Your Own Earth has been the inspiration and motivation for current and ongoing
interdisciplinary research grant proposals on paleoclimate modeling, as well as hardware and software for climate models to speed up computations and to be more energy efficient.

LOOKING FORWARD. The creation of Build Your Own Earth has led to an invigoration of teaching Earth system science at the University of Manchester. The concepts of planetary evolution, natural climate change, sedimentary environments, atmospheric and ocean general circulation, and paleontology—all of which were covered within our introductory course in the past—can now be integrated more effectively through Build Your Own Earth. Such effort has already started and more is planned. Each year, Build Your Own Earth inspires an undergraduate or two to develop a dissertation project based around climate modeling. Build Your Own Earth will continue to grow in the future, pending funding and personnel availability, with more paleoclimate simulations at higher spatial and temporal resolution. The tool is freely available for all to use and incorporate into their classroom teaching (www.buildyourownearth.com).

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REFERENCES


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