A Hitchhikers Guide to the Black Arts
(of Earth system modelling)
II: Snowball Earth and climate hysteresis in *c*GENIE

Stuff to keep in mind:

- Polar bears would have eaten all the penguins if sea-ice stretched from pole to pole.
- The threshold for getting out of bed on a cold morning is much greater than that required to get into bed in the first place. It can thus be demonstrated mathematically that a state of permanent lie-in is not only possible, but may be inescapable.
- Don't believe everything you read in Nature.
- Or Terra Nova.
- Certainly nothing you read on the internet ...

Relevant reading:

Hoffman et al. [1998] (*Science* **281**, 1342)
→ The snowball Earth hypothesis.

Caldeira and Kasting [1992] (*Nature* **359**, 226–228)
→ How do we get out of this mess now?

Donnadieu et al. [2004] (*Nature* **428**, 303-306)
→ The importance of continental configuration in triggering a snowball Earth?

Hoffman and Schrag [2002] (*Terra Nova* **14**, 129-155)
→ Snowball review.

Hyde et al. [2000] (*Nature* **405**, 425-429)
→ Model analysis of the inception of a snowball Earth and ice-albedo thresholds.

Ridgwell et al. [2003] (*Science* **302**, 859-862)
→ Global carbon cycle issues.

Stone and Yao [2004] (*Climate Dynamics* **22**, 815–822)
→ Climate hysteresis (in solar constant space) modelling.

Voigt and Marotzke [2010] (*Climate Dynamics* **35**, 887–905)
→ Modelling the transition into a snowball Earth.

Voigt et al. [2010] (*Clim. Past Discuss.* **6**, 1853–1894)
→ Modelling the transition into a snowball Earth.

There is also a website with a comprehensive literature listing of snowball Earth things:
http://www.snowballearth.org/

8. Brrrrrrrrrrr – it's chilly on ... snowball Earth!

8.0 To illustrate how easy (*lol*) it can be to configure an Earth system model such as *c*GENIE and explore the behavior of the Earth system and its response to perturbation – you are going to induce an extreme cooling of climate and see what happens. Solar output was weaker was during the late Neoproterozoic, a time when the Earth experienced a series (2-ish) of extreme glaciations. Thus, retaining a mild climate state must have been dependent on sufficient CO_2 and/or CH_4 in the atmosphere. (Sort of the opposite of the problem we have today.)

8.1 Before you can run the model in this new configuration, you first need to get rid of the current *c*GENIE executable (the program that is created by the FORTRAN compiler from the source code) because it is specific to the original model configuration (which had the modern continental positions). To do this, (from `genie-main`) type:

```
$ make cleanall
```

Note that you only have to do a '`make cleanall`' when changing the resolution of the model (either spatially, or the number of dissolved 'tracers' in the ocean, but it is sometimes safer to also do it following a major change to the configuration of the model (e.g., altered continents).

To run the model (say for 100 years), you will need to enter the following at the command line:

```
$ ./runcgenie.t48.sh cgenie_eb_go_gs_ac_bg.p0650c.NONE.t48
 LABS exp4_snowball 100
```

Note that you are now using a different *base-config* file (`cgenie_eb_go_gs_ac_bg.p0650c.NONE.t48`), which defines the basic configuration of the continents, ocean bathymetry, number of ocean *tracers* (just T and S here) etc. as well as a new *user-config* file (`exp4_snowball`) which specifies the finer details of the experimental design.

If you follow the changes with time in ocean surface temperature (SST) or sea-ice cover, the rapid initial adjustment indicates that you are far from steady-state.

You will see that the run-time output is a little different to before – this is because the carbon cycle has not been 'selected' (i.e., the carbon cycle is disabled) and so only climate-relevant variables are being displayed.

8.2 A spun-up state has been provided for you, which can be used as a restart (as before):

```
$ ./runcgenie.t48.sh cgenie_eb_go_gs_ac_bg.p0650c.NONE.t48
 LABS exp5_snowball 100 exp0_snowball_SPINUP
```

You now initially have a (relatively) stable climate (because you are starting from a previous state).

8.3 Go to the results directory of the experiment and open up the 2-D NetCDF file (from the `biogem` directory). View the topography (ocean depth) field (`grid_topo`) – land is shown in grey by default. Also by default, Panoply will try and plot on the modern continental outline – turn this off by selecting <`none`> for Overlay in the Map tab. The model has been configured for an idealized super-continent, positioned symmetrically about the Equator. Of course, this is pretty unrealistic. But the further you go back in time, the more uncertain it becomes as to exactly where and in what orientation the continents were. Sometimes modelers have to resort to somewhat idealized experiments if the uncertainties are too great. In addition, one can conduct sensitivity experiments to test whether the continental configuration is important to the results – in this case, we might have had a second alternative configuration with a super continent positioned over a pole. And/or we could have had a set of very fragmented continents.

8.4 Throughout – think about:

- *Is the model configuration and experimental design 'realistic' ... ?*
- *What is 'missing' in the model and what might the implications for your predictions and conclusions be?*
- *Are the simulations being run for sufficiently long? Why not if not (i.e., justify your choices of parameter values and experimental assumptions)? How might the results and conclusions be biased (if at all)?*
- *How would you test model predictions and your overall conclusions?*
- *How could the experimental design be improved?*

Now ... you are going to see if you can find the atmospheric CO_2 concentration (or rather, radiative forcing equivalent) that would lead to a 'snowball Earth' state in the Neoproterozoic ...

To do this, you are going to edit the file that controls the specific details of the experiment. This is the *user-config* file. From the `genie-userconfigs/LABS` directory, open one of the snowball experiments (e.g. `exp5_snowball`) in the SciTE text editor. At the top you should see:

```
#
#
# --- CLIMATE -----------------------------------------------------------
#
# solar constant reduced by 5.6% for late Neoproterozoic: 1285.92 W m-2
ma_genie_solar_constant=1285.92
# set no seasonal cycle
ea_dosc=.false.
go_dosc=.false.
gs_dosc=.false.
# scaling for atmospheric CO2 radiative forcing, relative to 278 ppm
ea_radfor_scl_co2=20.0
```

Each line that is not commented out (i.e., no #) contains a parameter of the format:

`PARAMETER=VALUE`

The value of each parameter can be edited to form a new experiment. (Additional parameter value specifications can also be added, or existing ones deleted.)

For instance, the line:

`ma_genie_solar_constant= 1285.92`

specifies a reduction in the solar constant of about 6% (from the modern value of 1368 W m^{-2}), appropriate for the late Neoproterozoic, while the line:

`ea_radfor_scl_co2=20.0`

specifies a radiative forcing of climate by CO_2 equivalent to ×20 modern (20×278 = 5560 ppm).

Edit the value of `ea_radfor_scl_co2` (lower or higher) and save the file. Re-run the experiment to see whether sea-ice extent is approaching a new steady state.

View some of the appropriate time-series and time-slice files. Informative time-series variables might include (but not necessarily be limited to): atmospheric and ocean temperature, sea-ice cover and thickness. For the time-slice data: atmospheric and ocean surface temperature and sea-ice extent (2-D biogem NetCDF file) may be informative (the full 3D field of ocean temperature is contained in the 3-D biogem NetCDF file).

How low does CO_2 (radiative forcing) have to be to trigger a 'snowball'?

HINT 1: You can make copies (`cp` command) of the *user config* file (e.g. `exp4_snowball`) with different names differently, e.g., `exp4a`, `exp4b`, `exp4c`, …) and in each copy, specify a different radiative forcing assumption. By submitting the experiments to the cluster will allow you to run all these experiments simultaneously.

HINT 2: Be careful with the default 'auto-scaling' feature in Panoply. At near complete sea-ice cover, you may find Panoply scaling min and max sea-ice between 99.1 and 99.9% or something – it always tries to maximize color contrasts be default, but that may not be helpful and in some instances it will be misleading to present results like this. Often in series of model experiments in which multiple (e.g., differing CO_2) predictions are presented, they will be scaled identically (hence allowing direct inter-comparison).

Note: DON'T PANIC! If the model 'crashes' – once it is in a 'snowball' state, the sea-ice steadily builds up and gets thicker and thicker. Because of the low resolution and relatively long time-step used here (chosen to accelerate the exercise), at some point it becomes impossible to adequately solve e.g. heat diffusion through the sea-ice and the model crashes. (It is at least an indication that a snowball state has been achieved.)