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. Also note that the run script (`runcgenie.t48.sh`) has changed – this one is designed specifically to go with the lower resolution and faster-running *base-config*. (The difference is basically just that the time-steps in the model are specified as being twice as long, i.e., the same number of time-steps covers twice the ground!)

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.

Sea-ice cover, not initially present, does not often appear until sometime after year 10. Why? (Hint: The ocean is initialized at a temperature of zero degrees C everywhere. What temperature does seawater freeze at?)

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. For instance, *Hoffman and Schrag* [2002] discuss the potential importance of continental configuration, while the entire hypothesis of

Donnadieu et al. [2004] rests on specific details of the continental configuration being realistic. Other useful 2-D variables to view are surface air temperature and sea-ice extent (and/or thickness). Ocean surface temperature and salinity can be viewed in the 3-D NetCDF results file.

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. You may want to try even longer simulations if it becomes clear that the model is still far from steady-state. You can judge how close to equilibrium things have got by following (and/or plotting) the evolution of e.g., global surface air temperature or sea-ice extent (both time-series files). (Note that you *might* want to run the experiment longer than 100 years …)

How far towards to Equator does the sea-ice limit encroach?

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).

Try and answer the question (to an appropriate degree of accuracy):

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.)

8.5 Test whether the thresholds dependent on seasonality. In the basic *c*GENIE snowball model configuration there is no seasonality. Does this matter? To include seasonal insolation forcing,set:

```
ea_dosc=.true.
go_dosc=.true.
gs_dosc=.true.
```

8.6 You can also test how important (or not) continental configuration is to your results. You can utilize a different (but also highly idealized) configuration with a polar (rather than equatorial) super-continent by changing the *base-config* as follows (and creating a new (copied) *user-config*):

```
$ ./runcgenie.t48.sh genie_eb_go_gs_ac_bg.p0650d.NONE.t48
 LABS exp5_snowball 100
```

(Again: take care not to confuse '`l`' and '`1`' – the last two characters are 'el'-'one'.)

Note that you will need to do a '`make cleanall`' first because you have changed the physical configuration of the oceans and continents. Also note that there is no *restart* provided for this particular configuration, so maybe you are not making a fair test in contrasting an equatorial supercontinent started from a stable climate state with a polar supercontinent started from 'cold'?? (In designing experiments, ideally one would change only one thing at a time in making comparisons; otherwise it becomes ambiguous which of more than one factor explains any difference in results.)

8.7 Finally, once you are happy about the controls on the snowball threshold, try and answer:

How high does (CO_2) radiative forcing have to be to <u>escape</u> from a snowball?

If you run the model just long enough to fall into a snowball, you can use that experiment as a *restart* and be able to carry out a series of experiments with increasing radiative forcing, all starting from the snowball state you have created. Defining the radiative forcing / climate path going out of a snowball would complete the hysteresis loop that *Hyde et al.* [2000] could only generate for going into a snowball, but still got a Nature paper out of ;)

HINT 3: The 'ideal' *restart* climate state is one which has not spent very long in a snowball state – the longer the climate is in the deep glacial state the thicker the sea-ice (and hence greater ice volume) will become and the longer it will take to exit. (Often if the sea-ice gets too thick the model will simply crash.) Once you have determined (from 8.4) the threshold to enter a snowball state, create an experiment that crosses this threshold but does not spend more than a few years in it – you may need to run the model with a long run-time, stopping it once it snowballs, then re-run with run duration just sufficient to enter into the snowball. (Spending e.g., decade or so in the snowball state is OK – it does not have to be fine-tuned to within a month!)