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 during the late Neoproterozoic, a time when the Earth experienced a series (2 ish) of extreme glaciations. Thus, having a mild climate state to start with must have been dependent on sufficient CO_2 and/or CH_4 in the atmosphere and hence presumably highly elevated compared to the modern World, so sort of the opposite of the problem we have today …

8.1 First off: The model code has been adjusted very slightly and you'll need to 'update' your installation of the model. Simply change (`cd`) to the `cgenie` directory (not home, and not genie-main where you run the model from) and type:

```
$ svn update
```

You will also need a new *restart* file that has been created (a pre-run 10,000 year spin-up). You obtain this in a similar way to before (Section 7.2). The full instructions are repeated here, but in future you will be given only the URL (web address) of the file and expected to go fetch it and unpack it without further tedious wordage.

Change to the `cgenie_output` directory, and type:

```
$ wget  http://www.seao2.info/cgenie/labs/EC4.2012/exp0_snowball_SPINUP.tar.gz
```

This downloads an archived/compressed copy of the *restart* (`exp0_snowball_SPINUP.tar.gz`) from a location on the interweb. Extract the contents of this archive by typing:

```
$ tar xfzv exp0_snowball_SPINUP.tar.gz
```

8.2 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.t100.sh cgenie_eb_go_gs_ac_bg.p0650a.NONE.t100
 LABS exp4_snowball 100
```

Note that you are now using a different *base-config* file (`cgenie_eb_go_gs_ac_bg.p0650a.NONE.t100`), which defines the basic configuration of the continents, ocean bathymetry, number of ocean *tracers* (just T and S here – no biogeochemical tracers such as dissolved carbon) 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.

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

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

```
$ ./runcgenie.t100.sh cgenie_eb_go_gs_ac_bg.p0650a.NONE.t100
 LABS exp5_snowball 100 exp0_snowball_SPINUP
```

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

8.4 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 – you can 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.

8.5 Answer the question (to an appropriate degree of accuracy):

How low does CO_2 have to be to trigger a 'snowball'?

To do this, you are going to edit the file that controls the specific details of the experiment to test different assumptions about radiative forcing from CO_2. 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 a CO_2 equivalent of ×20 modern (20×278 = 5560 ppm).

Note that CO_2 is not being explicitly modeled in this experiment, but the long-wave radiative forcing associated with a specified concentration of CO_2 (as a ratio to modern concentrations) is being set instead.

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 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 …

HINT: You can make copies (`cp` command – see Appendix I in the first handout) 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.

8.6 For each experiment you want to be assessing how far towards the Equator the sea-ice limit encroaches through some of the time-series and time-slice files or even the on-screen summary lines (assuming running interactively rather than via a job submission to the cluster queue).

Informative time-series variables include (but not necessarily be limited to: atmospheric temperature and sea-ice cover. (Sea-ice thickness, on account of the simple physics in the model, low resolution and long time-step, can be a little bonkers at times, but sea-ice volume should be more trustworthy.)

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.)

For the time-slice data: atmospheric and ocean surface temperature and sea-ice extent (2-D biogem NetCDF file) may be informative.

HINT: 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 by default and will be at all helpful in this case.

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?*

In answering the question ('How low does CO_2 have to be to trigger a 'snowball'?') also think about what an appropriate degree of accuracy might be for your experiments. Just because computer models generally calculate to around 16 significant places of <u>precision</u>, does not mean you have 16 significant figures of <u>accuracy</u> (or realism). For instance – how many significant figures is the solar constant quoted to and what do you think is the uncertainty in this? Harder to judge is how the assumed (incorrect) continental configuration creates additional uncertainty, or the physics assumed in the ocean or sea-ice, or lack of snow on land …

Uncertainty associated with structure error in the model can be estimated to some extent and you'll be looking into this in the assessment exercise, but you can make a start here in terms of exploring the importance of different model assumptions by testing whether the (CO_2 radiative forcing) threshold to go into a snowball state is dependent on seasonality. In the basic *c*GENIE snowball model configuration there is no seasonality. Does this matter? For instance, to include seasonal insolation forcing, set:

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

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 ;)