# A Hitchhikers Guide to the Black Arts
## (of Earth system modelling)
## `Lesson #1:` snowball Earth

Stuff to keep in mind:

- Models ARE NOT the 'real World' (it is going to be pretty obvious this is the case here).
- Don't believe what you read in Nature or Science.

Relevant reading:

Snowball Earth and ice-albedo feedback & hysteresis

*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.

# 0. Readme

0.1 You will need to download a new *restart* file prior to embarking on the snowball Earth experiments.

To fetch this: change to the `cgenie_output` directory, and type (or copy and paste carefully from the PDF …):

```
$ wget http://www.seao2.info/cgenie/labs/Yale.2016/LAB_1.SPIN.tar.gz
```

This downloads an archived/compressed copy of the experiment `LAB_1.SPIN` – effectively, just an experiment (*spin-up*) that has been run for 10,000 years for you. Extract the contents of this archive by typing:

```
$ tar xfzv LAB_1.SPIN.tar.gz
```

A new experiment results directly will then appear as if you had just run the entire 10,000 year experiment yourself, and you could in fact have done so (remember to refresh the SSH window).

You'll then need to change directory back to `genie-main` to run the model.

# 1. Brrrrrrrrrrr – it's chilly on ... snowball Earth!

1.0 To illustrate how 'easy' 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 …

1.1 You are going to be running experiments similar to before and using the *restart*:

```
$ ./runmuffin.sh cgenie.eb_go_gs_ac_bg.p0650e.NONE LABS LAB_1.EXAMPLE 100
LAB_1.SPIN
```

but rather than use the provided experiment configuration file `LAB_1.EXAMPLE`, why not get into the habit of creating new and uniquely named *user-config* files (no harder than copying it and renaming it!). If you keep using the same experiment name, the results will be over-written each time. Also, be especially careful not to have 2 (or more) experiments running simultaneously with exactly the same name as they try and over-write each other in a somewhat entertaining way.

Overall: your task in this exercise will be to determine the radiative forcing (or $pCO_2$ equivalent) threshold required to drive the climate system into a full ice-covered ocean (snowball Earth) state. (Read the *Hyde et al.* [2000] paper.)

Useful 2-D (netCDF—Panoply) 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 (apologies for ocean temperature being in units of K …). You can also save the data seasonally if you like – see Section 5.2.3 in the User Manual (your configuration has 48 time-steps per year for the BIOGEM module).

Time-series (ASCII `.res` files) are useful for providing simple mean indicators of global climate such as global ocean fractional sea-ice covered.

Note that the model configuration of an idealized super-continent, positioned symmetrically about the Equator, 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. 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.

For this configuration, the solar constant is set weaker than modern by default to reflect the fact that the sun's output has increased with time and during the Neoproterozoic the solar constant would have been ca. 5% weaker. This is set by the parameter (hidden out of sight in the *base-config* file):

```
ma_genie_solar_constant=1285.92
```

(compared to a modern value of 1368 W $m^{-2}$)

Other questions to think about with regards to numerical modeling (and this experiment) are:

- *(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? For example, there is no land-surface scheme (and hence no concept of 'snow') in this particular configuration.*
- *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?*

1.2 To search for the atmospheric $CO_2$ concentration (or rather, radiative forcing equivalent) that would lead to a 'snowball Earth' state in the Neoproterozoic and answer the question:

'**How low does $CO_2$ have to be to trigger a 'snowbal**l'?'

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 in the SciTE text editor. At the top of the file you should see something like:

```
#
#
# --- CLIMATE ----------------------------------------------------------
#
…
# 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.) In this example, 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).

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

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 …

HINT: submitting the experiments to the cluster allows all the experiments to be run simultaneously.

1.3 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 fluctuate a little in area and volume at times.)

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.

In answering the question 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 precision, does not mean you have 16 significant figures of accuracy (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 …