2. Further ideas

2.1 How high does the (CO_2) radiative forcing have to be in order to escape from a snowball?

If you run the model with an appropriate radiative forcing to create 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 of *Hyde et al.* [2000]. Note that a good restart is one for which the experiment did not sit long in the snowball state before finishing. You can fine-tune the number of years the experiment is run for to achieve this.

Overall: think critically about the model configuration, the experimental design, and the nature of the scientific question (based on your background reading of snowball Earth). Some of the exploration/testing suggestions (above) may not necessarily give substantially different results. Such a finding would be as valid and interesting as determining an important dependence of a certain assumption, and would for instance indicate that the associated paleo uncertainties are not critical to model assessment of the question.

Always be prepared to justify all your choices for experimental design and model settings, e.g., range of radiative forcing assessed, continental configuration(s), solar forcing, use of *re-starts* (if any), run duration, etc. etc. etc. etc.

2.2 Feedback loop analysis following *Hyde et al.* [2000]

In order to quantify the snowball Earth hysteresis loop in *c*GENIE as per Figure 2 in *Hyde et al.* [2000] you will need to extract from the model 'meaningful' measures of climate (e.g., global surface air temperature, fractional sea-ice coverage) as a function of CO_2 multiples, CO_2 concentration, or (better) radiative forcing. For the latter, in cGENIE, the radiative forcing for a doubling of CO^2 is set at: 5.77 W m^{-2}. See: *Myhre et al.* [1998] (*Geophys. Res. Lett.* **25**, 2715–2718) and/or *IPCC* [2007] for more on what radiative forcing is and how it is related to a relative change in CO_2 concentration. Also, for making a comparison with *Hyde et al.* [2000] for going into the snowball, note that they plot the change in radiative with a 'cooling' as positive (a bit daft). Their baseline radiative forcing state (an anomaly of 0 W m^{-2}) you might assume is equivalent to 278 ppm and hence ~130 ppm is an approximately halving of CO_2 and hence creates ~5 W m^{-2} of cooling. (You might prefer to plot the radiative forcing change as warming being positive, which makes rather more sense ...)

For coming out of a snowball, because the CO_2 and hence radiative forcing threshold is so high compared to going in, you may want to be creative in the plotting (assuming attempting to combine both thresholds into a single plot) and, for instance, one might break the scale between the low radiative forcing interval spanning going in and the high one spanning coming out.

Another example is as per Figure 3,4 in *Stone and Yao* [2004] (*Clim. Dyn.* **22**, 815–822) (although here it is the solar constant rather than long-wave radiation forcing that is being varied).

2.3 Continental configuration

It was mentioned earlier that the position of the continents is an area of modelling uncertainty and might be important. You can test for this. Four alternative *base-configs* are provided which each define a different continental configuration:

1. `cgenie.eb_go_gs_ac_bg.wopol1.NONE` – **a single polar super-continent**, with an ocean resolution of 36×36 with 8 vertical levels. (Note potential 'l' and 1'1 confusion in 'wopol1'.)
2. `cgenie.eb_go_gs_ac_bg.wopol2.NONE` – **one continent at each pole**, with an ocean resolution of 36×36 with 8 vertical levels.
3. `cgenie.eb_go_gs_ac_bg.woreq1.NONE` – **a single Equatorially-centred super-continent**, with an ocean resolution of 36×36 with 8 vertical levels.
4. `cgenie.eb_go_gs_ac_bg.woreq2.NONE` – **two continents straddling the Equator**, with an ocean resolution of 36×36 with 8 vertical levels.

You can use tht same *user-config* file (`LAB_1.EXAMPLE`) as before as an experiment template and any of the alternative configurations can be run very similarly to as per before, i.e.:

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

Note that you are using a different *base-config* file name: `cgenie.eb_go_gs_ac_bg.xxxxx.NONE` here compared to Lab #1, where `xxxxx` is one of: `wopol1`, `wopol2`, `woreq1`, or `woreq2`.
Also note that no *restarts* are provided for these configurations. You may (or may not) want to create some (you will need to judge for yourselves how long to run the *restart* experiments for to achieve as close to steady-state as you think is 'sufficient'). Remember that *restarts* are just 'normal' experiments that have already been run.

Be careful that when changing from one *base-config* to another, the model re-compiles. Simply running the new configuration briefly is sufficient to ensure this. Experiments can then be safely submitted to a cluster queue. i.e. do not try and submit an experiment using a different *base-config* straight to the cluster queue without having run it (or a short version of the experiment you want) first (to ensure the model is re-compiled). This is also good practice – checking that a new sort of experiment and/or model configuration works as you intend and without hiccups.

2.4 Geothermal heat input

Finally, *c*GENIE will fairly happily build up sea-ice, apparently without limit (with the remaining wet ocean becoming progressively colder and more saline). In the real world, one might expect some sort of limit to the maximum thickness achieved as the heat diffusion across a progressively greater thickness of sea-ice approaches the heat input at the bottom of the ocean from geothermal energy. Different modes of ocean circulation are also possible if one considers heating from the bottom as well as cooling (and brine rejection) from the top and which might affect the entry into or exit from a snowball state.

In the experimental setup you have been given, a geothermal heat input is specified in the ocean circulation module via the following parameters

```
bg_ctrl_force_GOLDSTEInTS=.TRUE.
bg_par_Fgeothermal=100.0E-3
```

The first enables the temperature and/or salinity of the ocean to be modified by processes other than redistribution via ocean circulation and exchange with sea-ice and atmosphere (i.e. to impose external forcings). The second sets the geothermal flux in units of W m^{-2}. (Note that in the Neoproterozoic, the geothermal heat flux could have been somewhat higher than modern. How much? A question for Google…)

An appropriate research question might be to determine in radiative forcing vs. geothermal space (and requiring a 2D grid of parameter combinations to be created and submitted to the cluster): the equilibrium sea-ice thickness and region in which a snowball solution is not possible. However, more simply and suitable to a short workshop: **How much of a difference to the estimated entry and exit thresholds of radiative forcing, does the inclusion of a geothermal input make?** e.g what happens if you set it to zero? What about 10 times modern (or more, although *extreme* seafloor heating can cause numerical instability)?