

A Hitchhikers Guide to the Black Arts (of Earth system modelling)

Va: How long is 'forever'?

Relevant reading:

Archer, D., *et al.*, [2009] (*Annual Reviews of Earth and Planetary Sciences* **37**, 117-134)

→ time-scales of CO₂ draw-down (as a model intercomparison exercise)

Ridgwell and Hargreaves [2007] (*Global Biogeochemical Cycles* **21**, doi:10.1029/2006GB002764)

→ description and calibration of the sediment model component and response to fossil CO₂ release

Chikamoto, M. O., K. Matsumoto, and A. Ridgwell [2008] (*JGR* **113**, doi:10.1029/2007JG000666)

→ deep-sea CaCO₃ sediment and atmospheric CO₂ response to AMOC shutdown

Panchuk, K., A. Ridgwell, and L. R. Kump [2008] (*Geology* **36**, 315-318)

→ configuration of (c)GENIE for Palaeogene marine carbon cycling; assessing PETM CO₂ release

Ridgwell [2007] (*Paleoceanography* **22**, doi:10.1029/2006PA001372)

→ description of sediment core modelling; application to the interpretation of PETM CCD changes

Copies of these references can be obtained from the 'usual places' (i.e., 'journals!'), or from:
www.seao2.info/pubs.html or <http://www.genie.ac.uk/publications/papers.htm>.

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12. The long tail of CO₂ and other tales from the sediments

12.0 You will be using a 'modern' configuration of cGENIE, but ... it is rather more idealized than you have seen for the modern Earth in previous Labs (although not quite as idealized as for the snowball Earth experiments). It also differs in that in addition to having an ocean carbon cycle (which was omitted from many of the previous Lab experiments), it includes a representation of deep-sea sediments and interaction between the preservation and burial of CaCO₃ and ocean chemistry plus balance between weathering and sedimentary burial. For an over-view of the sediment model and what time-scales and nature of carbon cycle interaction between ocean and sediment you can expect – read: *Ridgwell and Zeebe [2005]* and *Ridgwell and Hargreaves [2007]*. Note that you will be using a new cGENIE configuration, so before you forget ... you need to run a `make cleanall` You will also be using a different 'run genie' script: `runcgenie.t48.sh` when running the model (it configures different (faster) time-stepping).

12.1 Take the new model for a test drive by running on from the *restart* provided:

`exp0_glacialALT_SPINUP`. This is a steady-state climate+carbon cycle experiment that includes the deposition of CaCO₃ in deep-sea sediments and the balance between weathering (solute input to the ocean) and burial (output). Try running ('briefly', but 100 years would not be too tedious for this faster configuration!):

```
$ ./runcgenie.t48.sh cgenie_eb_go_gs_ac_bg_sg_rg.p0000e.BASESFe.t48  
LABS exp12_glacialALT 100 exp0_glacialALT_SPINUP
```

Note that the *base-config* (`cgenie_eb_go_gs_ac_bg_sg_rg.p0000e.BASESFe.t48`) is different from before and specifies the use of a sediment model 'sg' in GENIE for instance. It also includes an iron cycle alongside phosphate as a limiting nutrient (the 'Fe' bit) and takes fewer time steps per year ('t48'). In fact, you'll notice that it is rather faster than many of the previous configurations :)

(Don't worry about the 'glacial' bit in the filenames – this configuration has, by default, modern boundary conditions, but is designed for glacial experiments via a simple parameter adjustment.)

The degraded resolution (and fewer time-steps per year) is important in being able to run cGENIE on sediment and hence glacial-interglacial time-scales (see *Ridgwell and Hargreaves [2007]*) and within a reasonable time-scale (i.e., the time available to you for carrying out some glacial CO₂ research using the model). Unfortunately, that the resolution is rather more degraded than previously means that you will need to be aware of additional limitations and caveats associated with this configuration (these limitations and caveats are left for you to identify and take on board).

The *user-config* `exp12_glacialALT` is set up with the global carbon cycle is 'open' – that is to say, that there is an input of carbon (and alkalinity) to the ocean from weathering, and a loss due to preservation and burial of CaCO₃ in deep-sea sediments. Depending on the state of ocean chemistry (and biology) and weathering, these two fluxes (input and output) do not have to balance, and hence ocean carbonate chemistry (and in turn, atmospheric pCO₂) can change with time. The spin-up may not have the two fluxes (input and output) perfectly balanced and hence before you run any experiments you might want to confirm whether the *spin-up* provided really is adequately 'spun-up'.

(Note that a residual drift can be dealt with if it is relatively small and near linear and you have a control experiment, because any experiment you carry out will likely also incorporate (or be biased) by the same residual drift. Hence running a control gives you something to directly contrast with – your experiment minus the control (e.g., a difference map or simple subtraction of global numbers) will give you the effect of whatever parameters you changed in the experiment and corrected for any drift. In previous exercises we were a bit lazy, and difference maps were often created with respect to year 1 of an experiment – strictly, they should have been created relative to the same year of a parallel control experiment, i.e., results at year 100 should have been contrasted with the year 100 results of the control.)

12.2 There is a whole new set of additional outputs from this configuration of cGENIE, including sediment output (from the 'SEDGEM' module). For instance, the composition of the sediments only at the very end of a model experiment (hence unlike *BIOGEM*, which saves a series of *time-slices*

long) is saved by the *SEDGEM* module – kill a run before this, and you will get no (or little) output. 2D (e.g. surface sediment properties) results can be found in the *sedgem* subdirectory of your experiment directory and in a netCDF file called *fields_sedgem_2d.nc*. (Note that there is some duplication of results saving, because a series of *time-slices* of sediment composition are also saved in the 2D biogem netCDF file *fields_biogem_2d.nc* alongside with sea-ice extent etc.). The *time-series* file: *biogem_series_sed_CaCO3.res* also contains information about how the mean CaCO₃ content of surface sediments evolves with time.

For instance, the 2D distribution of wt% CaCO₃ – which is the weight fraction of calcium carbonate (CaCO₃) in the surface sediments of the deep ocean (i.e., how much plankton carbonate shell material is there compared to other stuff in the mud at the bottom of the ocean?) is saved under a variable called: *sed_CaCO3*. How much carbonate material there is tells you both something about how many carbonate shell secreting plankton were living at the ocean surface above and what is the chemistry of the deep ocean like that these tiny shells were preserved and did not dissolve. To gauge to what degree the faster configuration of *cGENIE* might provide an adequate representation of the interaction between ocean chemistry and sediment composition (e.g., in CaCO₃ buffering of CO₂ release and 'carbonate compensation'), the output should be contrasted to observational-based maps as well as (higher resolution) model results (e.g., as presented by *Ridgwell and Hargreaves [2007]*). Appreciate that *cGENIE* does not reproduce reality ... particularly at this lower resolution, but does it get the broad patterns right (is it more right than wrong, or more wrong than right)? Do you think the model-data misfits might be important? (Note that there is a reconstruction of the glacial pattern of CaCO₃ in sediments that is available and may be of use in constraining your glacial CO₂ hypothesis, or at least testing it against data.)

- 12.3 Because you are now considering a rather more complex carbon cycle than before (i.e. now including a number of additional, mostly sediments/weathering processes), it is worth conducting a number of idealized perturbations of the global carbon cycle to get a feel for the sensitivity and time-scale of the system response.

For instance – one illustrative experiment, and which has a parallel to experiments you have conducted previously, is to add a pulse CO₂ release to the atmosphere and track the consequences for atmospheric *p*CO₂ and ocean chemistry (particularly 'alkalinity'), and now also e.g. deep sea sediments. A forcing has been provided for this, differing from before in that a (constant) dust flux to the ocean surface is required in order to provide the micro nutrient iron (the Fe bit):

```
bg_ctrl_force_oldformat=.false.  
bg_par_forcing_name=' p0000e_FeMahowald2006modern_FpCO2_Fp13CO2 '
```

The CO₂ emissions is in the form of a unit (PgC) 1 year long pulse, which you will have to scale as before, e.g.:

```
bg_par_atm_force_scale_val_3=5000.0  
bg_par_atm_force_scale_val_4=-27.0
```

for a 5000 PgC total release (and comparable-ish to *Ridgwell and Hargreaves [2007]*).

Run the model for as long as you dare (or can be bothered) – 1,000 or 2,000 years might be just enough as a minimum to start to see impacts on deep-sea sediments, but 5,000 or 10,000 years would be better. (You can always submit this to the cluster queue and get on with something else.) FYI: 10,000 years is going to take something like an hour.

Plot the time-series of e.g. atmospheric *p*CO₂ and compare to the (much shorter experiments) you have carried out before with a simple ocean+atmosphere only system. Compare how quickly atmospheric *p*CO₂ decays compared to previously GENIE papers (e.g. *Ridgwell and Hargreaves [2007]*) or other models (e.g. *Archer et al. [2009]*) (see: <http://www.seao2.info/pubs.html>) and e.g. how the sediments respond (e.g. the *time-series* of sediment CaCO₃ content). If you have a comparable experiment from **Lab IVa** you could also compare directly with that (but note that the model configuration from before differs not only in having no sediment and weathering component, but is also higher resolution which may additionally affect your results).

To properly (quantitatively) appreciate the role of ocean-sediment interaction (and weathering) and controlling atmospheric *p*CO₂, you need to contrast these experiments with as similar a model

configuration as possible, except one having no sediments (or weathering). You can achieve this quite simply: create a new *user-config* and edit the lines:

```
# set an 'OPEN' system  
bg_ctrl_force_sed_closedsystem=.false.
```

to:

```
# set a 'CLOSED' system  
bg_ctrl_force_sed_closedsystem=.true.
```

(You do not have to edit the comment line (#) but it will help you remember what you have done.) What this line does is to force the model to always balance CaCO_3 preservation and removal in marine sediments with CaCO_3 weathering – i.e. the balance (or imbalance) between sediments and weathering is not allowed to change ocean chemistry and hence acts exactly the same as a configuration without any sediments or weathering (as used before).

By comparing the two experiments: can you deduce the effect of the sediments in modulating the atmospheric $p\text{CO}_2$ decline? E.g. compare the $p\text{CO}_2$ time-series. Also view the sediment distribution (of CaCO_3): what are the impacts on sediment composition for the experiment with an ‘open’ system? The time-series file of mean global sediment composition

`biogem_series_sed_CaCO3.res` (wt% CaCO_3) may help illustrate what is going on here.

Note that the way the ‘closed’ system is constructed, a response of the sediments is predicted and saved in the output, even though it is not allowed to affect chemistry or atmospheric $p\text{CO}_2$.

12.4 The model also generates artificial sediment ‘cores’ (e.g. see: *Ridgwell [2007]*) and hence what one might expect to see of your applied perturbations recorded in a sediment core recovered from the ocean floor. In the `sedgem` results sub-directory – you’ll see a series of files named:

`sedcore_?????.res`, where `????` stands for the (i,j) grid point location on the ocean floor in the model, counted exactly as per for the fresh water and numerical tracer flux forcing in **Lab III**.

(Ignore the files: `sedcoreenv_?????.res` – these record how bottom water and surface sediment properties vary at each (i,j) grid point location with time but this is not the same as what is recorded in a sediment record – why? What additional processes are occurring in the sediments that may change how an e.g. rapid change occurring in the ocean is actually recorded?)

The locations of these cores are stored in a little ASCII ‘map’ of the ocean in the directory:

`~/cgenie/genie-sedgem/data/input`

and the file for this experiment is called: `p0000e_save_mask.36x36x8`.

Simply be editing (using the ASCII text editor) a ‘0.0’ to a ‘1.0’, you can get the model to generate and save a sediment ‘core’ at that location.

Open one of the `sedcore_?????.res` files. You’ll see a bunch of columns. On the left hand side, are columns detailing:

- # – sediment layer number (counting down).
- `db`s (cm) – (cumulative) depth below surface, measured from the sediment surface to the mid-point of each sediment layer (cm).
- `th` (cm) – thickness of each sediment layer (cm).
- `CaCO3_age` – the mean age of CaCO_3 particles in a sediment layer. Note that this will not be defined if there is no CaCO_3 preserved.
- ... then some alternative ways of assigning a chronology to a sediment core ... (ignore).
- `Phi` (`cm3 cm-3`) – sediment layer density (as if you cared!).
- `POC` and `POC_13C` – mean organic matter content of each sediment layer and its $\delta^{13}\text{C}$. But note: in this configuration no organic matter is preserved (hence all zeros for POC).
- `CaCO3` and `CaCO3_13C` – mean CaCO_3 content (wt%) of each sediment layer and its $\delta^{13}\text{C}$.
- `det` and `ash` – the wt% detrital and ‘ash’ contents of a layer (`ash` is used as a conservative numerical sediment tracer in order to mark the depth of the start of the experiment).
- `foram_p_13` and `foram_b_13` – ‘foraminiferal’ $\delta^{13}\text{C}$ tracers (planktic and benthic) – act exactly the same as per bulk CaCO_3 in terms of dissolution, but are assigned different $\delta^{13}\text{C}$ values (one at surface and the other at depth) and can utilize experimentally determined relationships between $\delta^{13}\text{C}$ and e.g. ambient saturation.

Obviously – you could plot e.g. CaCO_3 (or its $\delta^{13}\text{C}$) as a function of depth and/or age across and see how your carbon release experiment might be recorded in the marine geological record. How does this compare with e.g. the PETM?

You'll find that core `sedcore_1117.res` has the 'best' resolved (i.e., highest accumulation rate) record but maybe glance at them all. The locations were selected quasi randomly and different sites (or all possible model grid locations) could have been selected. If you wanted to add/change the locations at which sediment cores are extracted from the model data, this is set in the file:

`p0000b_save_mask.18x18x8` which lives in the directory: `cgenie/genie-sedgem/data/input`. It should be obvious(?) what is going on in this file ...

Note that the sediment cores reflect not only the material which has accumulated (or not, if it has dissolved ...) during the course of your experiment, but also the material that accumulated during the 50,000 year spin-up. AND, whatever material the sediment core was initialized with to start with. The large interval of first 100% detrital material below which everything is zero simply reflects the initialization of the sediment array in the model. Also note the ash 'peak' near the bottom of the stack (filled) sediment layers – this is a tracer to 'tag' the start of the model spin-up. If you look at the spin-up results (not your recent perturbation experiment) – the ash peak lies in a sediment layer with age 50,000 years. But why is there any ash deeper than the age corresponding to the start of the spin-up??? How can it get there?

- 12.5 Rather than driving an initial dissolution of CaCO_3 in deep sea sediments, the opposite (initial response) can be obtained by removing CO_2 from the atmosphere (implemented by negative rather than positive emissions). BE CAREFUL here, as for a pre-industrial atmosphere with 278 ppm CO_2 , you do not have a lot more than ~600 PgC in there to begin with. So either: remove less than 600 PgC, or remove the carbon over a little longer than 1 year – implement this either by editing the *forcing* files directly, or set a scaling parameter for the duration (see **Lab IVa**).

(Hint: a forcing for removing CO_2 simply has the opposite sign to an addition (emissions) forcing.)

Again – view the time-series of ocean composition (e.g. DIC, ALK, $\delta^{13}\text{C}$) as a function of time, plus mean sediment surface composition (wt% CaCO_3). Also view the sediment 'cores' and hence what in practice has been incorporated into accumulating sediments as a record of what is a very sharp perturbation at the ocean surface (and atmosphere).

How then is a event characterized by CO_2 removal from the system recorded differently from one characterized by CO_2 release? Are there different implications for constructing core age-scales and chronology, e.g. where in (core) 'time' does the excursion maximum appear to lie? Do all sediment locations show identical responses (i.e. does it matter what the initial wt% CaCO_3 of a sediment is?).

- 12.6 Finally, you might investigate other facets of the nature of the relationship between ocean and sediments (and weathering) as how climatic (biogeochemical) signals are encoded in the marine geological record.

For instance, you could explore the effect/importance of sediment 'bioturbation' (e.g. see *Ridgwell* [2007]). Whether the surface sediment layers are bioturbation or not is set by the parameter:

`sg_ctrl_sed_bioturb=.true.` – simply change to `.false.` in order to 'turn off' bioturbational mixing.