

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

Lesson x: 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

Lord, N.S., A. Ridgwell, M.C. Thorne, and D.J. Lunt [2015] (GBC DOI: 10.1002/2014GB005074)

→ time-scales of CO₂ draw-down

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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0. Readme

0.0 If you have not been through (and completed!) Session #0100 ('Fossil fuel CO₂ release and ocean acidification') will need to download a *restart* file prior to embarking on the experiments with modern ocean circulation.

To fetch this: change to the `cgenie_output` directory, and type:

```
$ wget http://www.seao2.info/cgenie/labs/Yale.2016/  
EXAMPLE._rwlma.PO4_S18x18.SPIN2.tar.gz
```

Extract the contents of this archive by typing:

```
$ tar xfvz EXAMPLE._rwlma.PO4_S18x18.SPIN2.tar.gz
```

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

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

1.0 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].

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

`EXAMPLE._rwlma.PO4_S18x18.SPIN2.tar.gz`. 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!):

```
$ ./runmuffin.sh cgenie.eb_go_gs_ac_bg_sg_rg_gl._rwlma.BASES  
LABS LAB_x.sediments 100 EXAMPLE._rwlma.PO4_S18x18.SPIN2
```

Note that the *base-config* (`cgenie.eb_go_gs_ac_bg_sg_rg_gl._rwlma.BASE`) specifies the use of a sediment model 'sg' in GENIE for instance.

The degraded resolution (and fewer time-steps per year) is helpful in being run cGENIE on geological time-scales within a reasonable time. It also utilizes a conceptual/idealized continental configuration (similar to as in the snowball Earth experiments).

The *user-config* `LAB_x.sediments` 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 *p*CO₂) 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.)

1.2 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 CaCO_3 buffering of CO_2 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 CaCO_3 in sediments that is available and may be of use in constraining your glacial CO_2 hypothesis, or at least testing it against data.)

- 1.3 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 CO_2 release to the atmosphere and track the consequences for atmospheric $p\text{CO}_2$ and ocean chemistry (particularly 'alkalinity'), and now also e.g. deep sea sediments. To the *user-config*, add the lines:

```
bg_par_forcing_name=' pyyyyz.FpCO2_Fp13CO2 '  
bg_par_atm_force_scale_val_3=8.3333e+016  
bg_par_atm_force_scale_val_4=-27.0
```

in order to achieve a 1000 PgC total release in a single year (or multiply by 5 to be comparable-ish to *Ridgwell and Hargreaves* [2007]) with an isotopic composition of -27‰ – appropriate for a fossil fuel carbon source. Methane derived carbon (e.g. as from hydrates) would be more like -60‰.

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 much 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 $p\text{CO}_2$ and compare to the (much shorter experiments) you have carried out before with a simple ocean+atmosphere only system. Compare how quickly atmospheric $p\text{CO}_2$ 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 CaCO_3 content).

- 1.4 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, there is a netCDF file which contains all the locations selected (if any) – `sedcore.nc`. These are not really aligned with latitude as the Panoply display might suggest – the locations are in fact distributed from all over the ocean (Panoply is being fooled in order to display them together). In the SEDGEM 2D netCDF file, these locations are marked in the netCDF variable `grid_mask_sedcore`. The locations of these cores are stored in a little ASCII 'map' of the ocean in the directory:

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

and the file for this experiment is given by the parameter: `sg_par_sedcore_save_mask_name`

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.

The `sedcore.nc` variables are displayed as a function of 'latitude'. Variables include:

- `phys_layer` – sediment layer number (counting down).
- `phys_depth` – (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).

- `age_CaCO3` – 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).
- `phys_porosity` – sediment layer density (as if you cared!).
- `sed_POC` and `sed_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).
- `sed_CaCO3` and `sed_CaCO3_13C` – mean CaCO_3 content (wt%) of each sediment layer and its $\delta^{13}\text{C}$.
- `sed_det` and `sed_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).

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?

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?

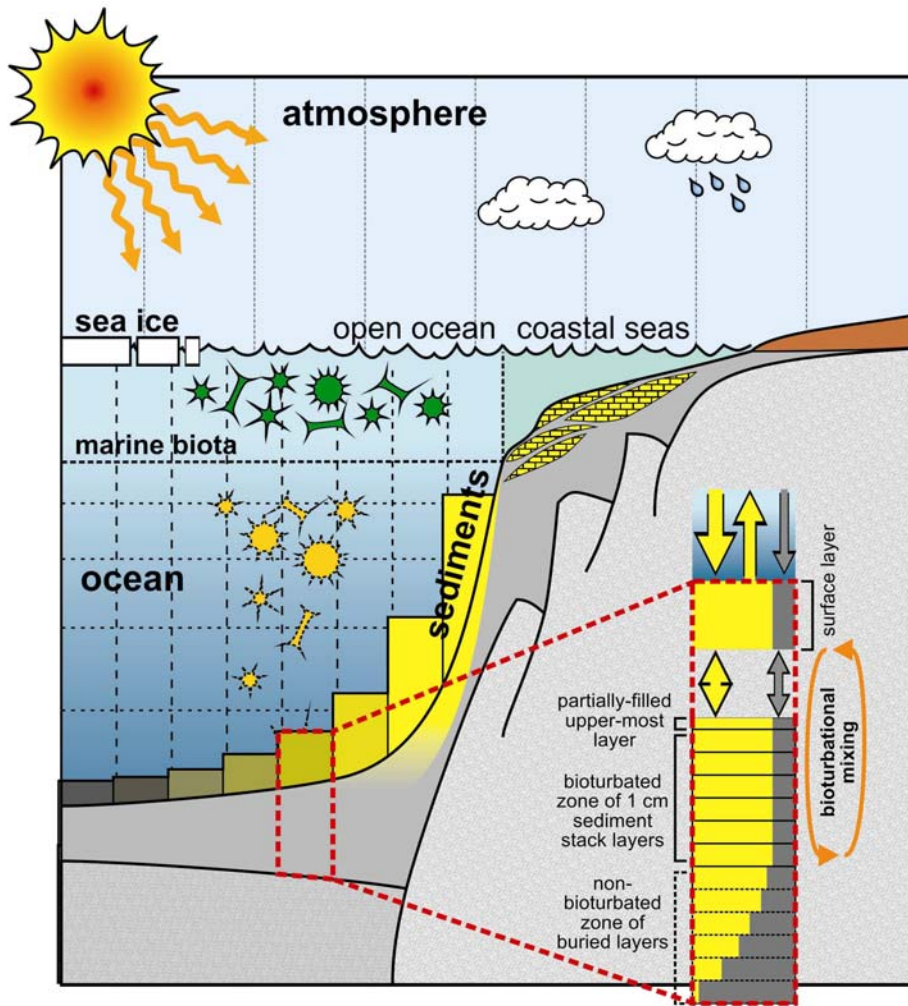
- 1.5 You can also explore the role of weathering and sensitivity of e.g. atmospheric $p\text{CO}_2$ and climate to this (as well as to volcanic CO_2 outgassing). Because the time-scale for seeing interesting stuff happen is now going to be l o n g ... you need some help. The *user-config* file:

`LAB_x.weathering` is provided which uses a ‘trick’ to accelerate the run-time (the new section # --- GEOCHEM ACCELERATION ---) ... see *Lord et al.* [2015].

Parameters of ‘interest’ that might be adjusted in the context of weathering and long-term controls on atmospheric $p\text{CO}_2$ (listed under # --- WEATHERING ---), include:

- `rg_par_outgas_CO2` – CO_2 outgassing rate in mol yr^{-1}
- `rg_par_ref_T0` – reference land surface temperature for weathering (C)

- 1.6 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.



Schematic of SEDGEM sediment component.