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

PART #1000: How long is 'forever'?

Relevant reading:

Archer, D., *et al.*, [2009] (*Annual Reviews of Earth and Planetary Sciences* **37**, 117-134)
→ time-scales of CO_2 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:10.1029/2007JG00066)
→ deep-sea $CaCO_3$ sediment and atmospheric CO_2 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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0.   Readme

0.0   If you have not been through (and completed!) Session **#0100** ('Fossil fuel CO_2 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/AWI.2013/ EXAMPLE.p0000e.PO4FeLiCa_S18x18.SPIN0.tar.gz`

Extract the contents of this archive by typing:

`$ tar xfzv EXAMPLE.worjh2.PO4Fe.HISTORICAL.tar.gz`

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

1. The long tail of CO$_2$ and other tales from the sediments

1.0 You will be using a 'modern' configuration of *c*GENIE, 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 CaCO$_3$ 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.p0000e.PO4FeLiCa_S18x18.SPIN0`. This is a steady-state climate+carbon cycle experiment that includes the deposition of CaCO$_3$ in deep-sea sediments and the balance between weathering (solute input to the ocean) and burial (output). Try running ('briefly', but 1000 years would not be too tedious for this faster configuration!):

```
$ ./runmuffin.sh cgenie.eb_go_gs_ac_bg_sg_rg_gl.p0000e.BASESFeLiCa
  LABS LAB.1000.sediments 1000 EXAMPLE.p0000e.PO4FeLiCa_S18x18.SPIN0
```

Note that the *base-config* (`cgenie.eb_go_gs_ac_bg_sg_rg_gl.p0000e.BASESFeLiCa`) 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. In fact, you'll notice that is it rather faster than many of the previous configurations :)

The degraded resolution (and fewer time-steps per year) is important in being able to run *c*GENIE 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 CO$_2$ 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 <u>you</u> to identify and take on board).

The *user-config* `LAB.1000.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 CaCO$_3$ 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*CO$_2$) 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 1000 should have been contrasted with the year 1000 results of the control.)

1.2 There is a whole new set of additional outputs from this configuration of *c*GENIE, including sediment output (from the '*SEDGEM*' module). For instance, the composition of the sediments only at the <u>very end</u> 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 $CaCO_3$ content of surface sediments evolves with time.

For instance, the 2D distribution of wt% $CaCO_3$ – which is the weight fraction of calcium carbonate ($CaCO_3$) 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 *c*GENIE 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 *c*GENIE 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 pCO_2 and ocean chemistry (particularly 'alkalinity'), and now also e.g. deep sea sediments.

The forcing specified in `LAB.1000.sediments`:

```
bg_par_forcing_name=' p0000e_FeMahowald2006modern_FpCO2_Fp13CO2'
```

is capable of introducing CO_2 to the atmosphere in addition to specifying a supply of new iron to the ocean surface. By default, CO_2 emissions are in the form of a unit (PgC) 1 year long pulse, which you will have to scale as before, e.g. to:

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

in order to achieve a 5000 PgC total release (and 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 pCO_2 and compare to the (much shorter experiments) you have carried out before with a simple ocean+atmosphere only system. Compare how quickly atmospheric pCO_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).

To properly (quantitatively) appreciate the role of ocean-sediment interaction (and weathering) and controlling atmospheric pCO_2, 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 pCO_2 decline? E.g. compare the pCO_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 pCO_2.

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 called: `p0000e_save_mask.18x18x8`.
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 $\delta^{13}C$. 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 $\delta^{13}C$.
- `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 $\delta^{13}C$) 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   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.
(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, $\delta^{13}C$) 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 an 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% $CaCO_3$ is?).

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.
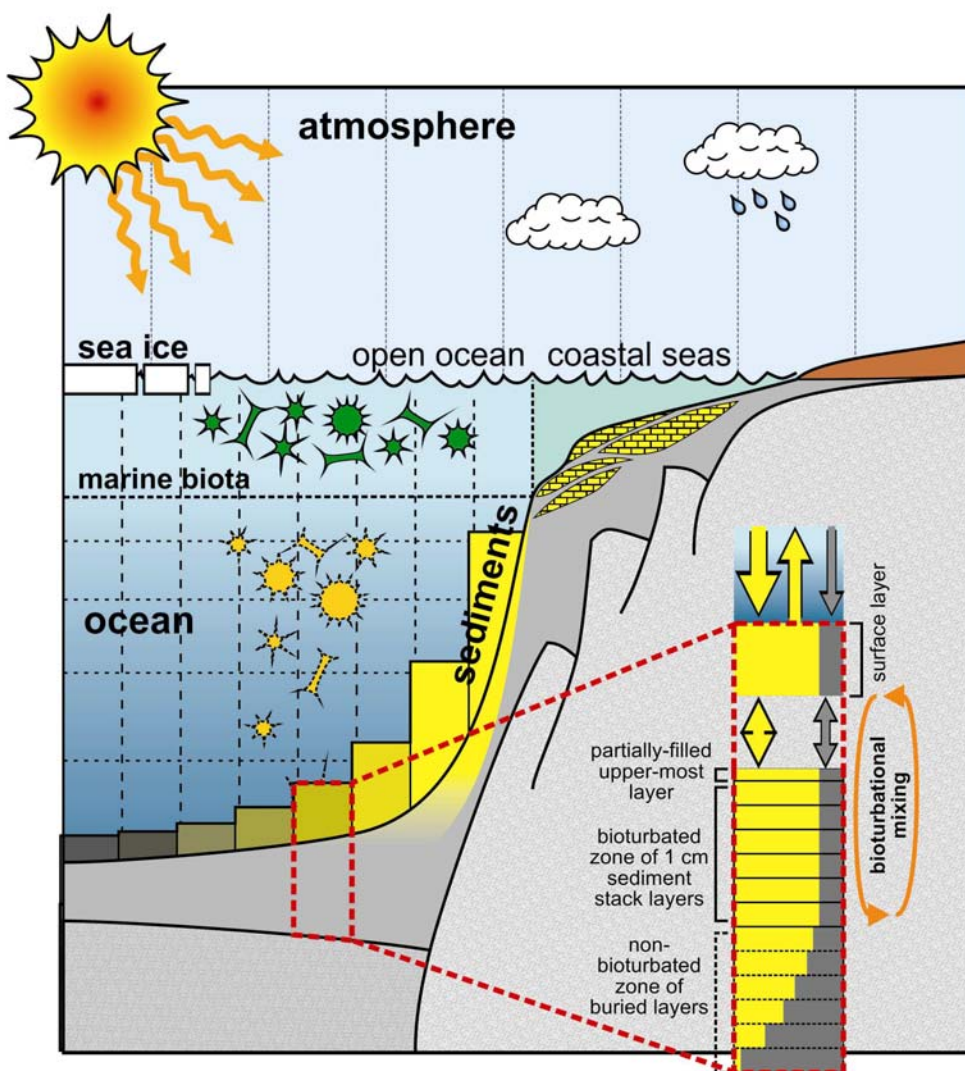
Schematic of SEDGEM sediment component.