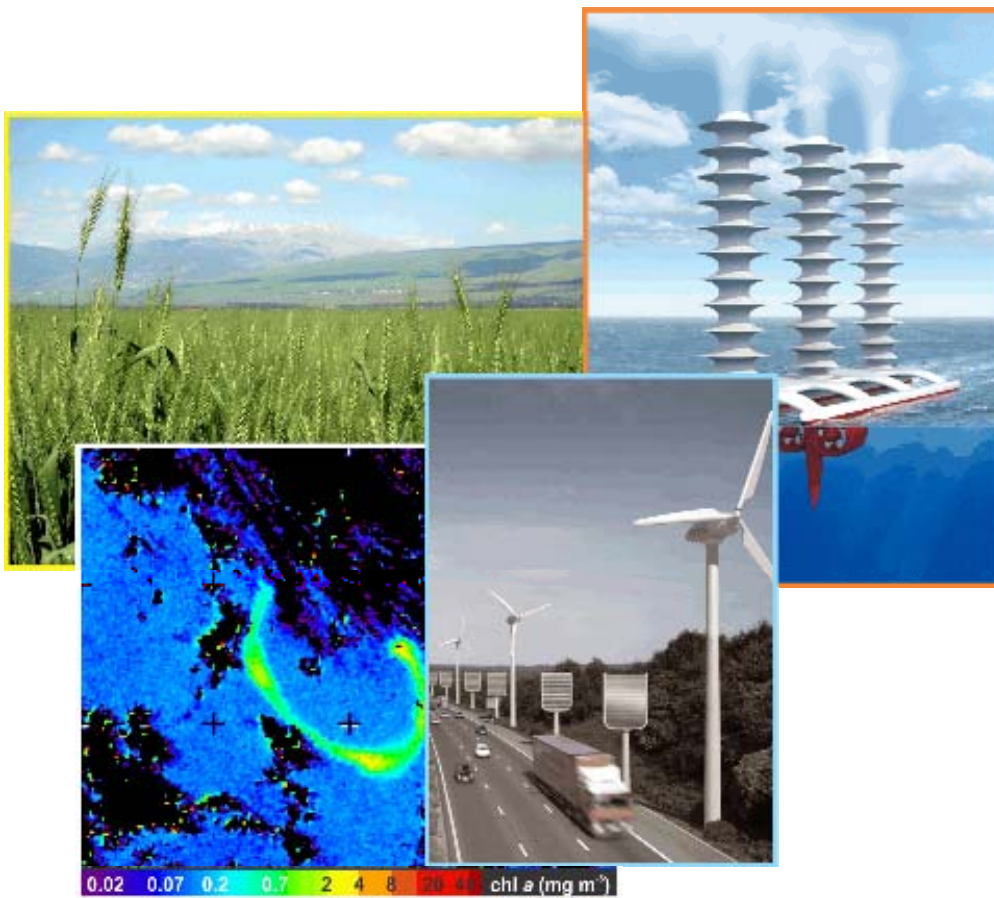


A Hitchhikers Guide to the Black Arts (of Earth system modelling)

V: Engineering the carbon cycle



11. Engineering the carbon cycle

11.0 For the next experiment(s) you are going to explore some of the ocean biological controls on atmospheric $p\text{CO}_2$ (and surface ocean geochemistry and ocean acidification) – highly relevant to the question of why atmospheric $p\text{CO}_2$ at the time of the last glacial was ~30% lower than both prior and following interglacials, as well as to ‘geoengineering’.

Model files have been updated centrally and as a result, you’ll need to update your own installation of the model. Simply change (`cd`) to the `cgenie` directory and type `svn update` as before.

You will also need a new `restart` file that has been created. Again as before -- change to the `cgenie_output` directory, and type:

```
$ wget http://www.seao2.info/cgenie/labs/EC4.2012/exp14_modernlores_SPINUP.tar.gz
```

Extract the contents of this archive by typing:

```
$ tar xfvz exp14_modernlores_SPINUP.tar.gz
```

(Remember to change directory back to `genie-main` before trying to run the model.)

11.1 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 includes co-limitation of marine production by iron (Fe).

To run the experiment for e.g., 100 years, starting from the `re-start`.

```
$ ./runcgenie.t48.sh cgenie_eb_go_gs_ac_bg.p0000e.BASESFe.t48 LABS  
exp15_modernlores 100 exp14_modernlores_SPINUP
```

You are going to be using this lower resolution and less ‘realistic’ version of `cGENIE`, as a faster substitute to the higher resolution model user previously to simulate the impact of fossil fuel CO_2 emissions, to first explore some of the controls on the cycling of carbon in the ocean (and hence on atmospheric $p\text{CO}_2$), and also how (deliberate) changes to the ocean carbon cycle might mitigate ocean acidification caused by fossil fuel CO_2 emissions. So this Lab falls into 2 parts:

- (i) Explore the sensitivity of atmospheric $p\text{CO}_2$ (and ocean geochemistry in general) to a number of perturbations of ocean carbon cycling, for which you will be making ocean biological pump parameter changes with no other (fossil fuel CO_2) forcings or perturbations to the system.
- (ii) Assess how these perturbations affect (and potentially mitigate), which will combine ocean biological pump parameter changes now with a background of fossil fuel CO_2 emissions.

Run the model for as long as you dare (or can be bothered), at least in the initial set of experiment where you do not have a specific time-frame of interest (i.e. anthropogenic time-scales) – 1,000 or even 2,000 years might be justified – assess what component of the ocean carbon cycle (or atmospheric $p\text{CO}_2$) adjust at what rate following the change in parameter values.

Spend a little time assessing to what degree you ‘trust’ this version (more or less or about the same) compared to the previous, higher resolution one. The greater degree to which it is less realistic, the greater degree to which you will have to take care in interpreting your results. (Ideally, you’d be assessing it directly with observations, rather than simply with another model.)

11.2 Some of the processes and controlling parameters included in the version of the model you have and which are relevant to the glacial CO_2 question (as well as potentially to geoengineering), and which you should explore the consequences of change (and the sensitivity or not of atmospheric $p\text{CO}_2$ and ocean acidification to them) are:

- **Iron fertilization.** Read up on this first, e.g., see references in *Kohfeld and Ridgwell [2009]*. The glacial was dustier than present, hence there can only have been increased aeolian iron supply to the ocean surface. However, what is not so clear is how important (relative to Fe being upwelled) aeolian Fe is today, let alone during the last glacial ...

Anyway: one way to increase the aeolian Fe supply to the ocean surface is simply to increase the solubility of the Fe in dust. This is controlled by the parameter:

```
bg_par_det_Fe_sol=0.0025
```

with the default being a global average dust Fe solubility of 0.25% (fraction == 0.0025).

Increasing it will increase the Fe input to the ocean surface everywhere (in direct proportion to the modern spatial pattern). The pattern of total aeolian Fe supply is recorded in the (2D BIOGEM) variable: `misc_sur_fFeTot_mol`, with the dissolved component under: `misc_sur_fFe_mol` (`misc_sur_Fe_sol` is the map of solubility, which in GENIE is not uniform in space – any idea what the reason for this assumption might be?).

(A glacially-explicit map of dust deposition could also be applied in place of the modern deposition map – if you would like to test this, I can create one, but note that there are very significant 'errors' in re-gridding dust maps to this highly simplified continental topography.)

[*There has been widespread discussion and there exists extensive literature on Fe fertilization in a geoengineering (carbon sequestration) context.*]

- **Remineralization depth.** There is no temperature control on the rate of bacterial degradation of sinking organic matter (see: book chapter + references therein) but the effect of lower ocean temperatures and a slower rate of bacterial degradation of organic matter can be simulated by specifying that particulate organic matter reaches greater depth before being remineralized (and CO₂ and PO₄ released back to the seawater). The parameter that controls the e-folding depth reached by particulate organic matter before remineralization is:

```
bg_par_bio_remin_POC_eL1=589.9451
```

Either edit this value (under heading: # --- REMINERALIZATION ---) or add a new line at the end of the *user config* file specifying the value you want. Units are m.

Read *Ridgwell et al.* [2007] for additional discussion of this parameter. See Figure 2-4 in *Ridgwell* [2001] (http://www.seao2.org/pubs/ridgwell_thesis.pdf) for an illustration of how the flux of particulate organic matter decreases with depth in the ocean, plus references therein.

There is also an associated parameter: `bg_par_bio_remin_POC_frac2`, which sets a fraction of organic matter that is assumed to settling through the water column completely un-altered (currently assigned a value of 0.045 == 4.5%), but this is arguably less appropriate to change than the remineralization length-scale of the more labile fraction (97.5% of exported particulate organic carbon).

[*Note that there may well be no simple parallel in a geoengineering context to this process, although industrially, coagulating and methods for accelerating the setting of often organic particles from solution are common.*]

- **Macro nutrient inventory and uptake.** Suggestions have been made that nutrients were used more efficiently during the LGM, meaning that for the same nutrient uptake at the surface more carbon was exported to depth in the ocean. See: *Omta et al.* [2006]. There are also a bunch of (relatively old) hypotheses concerning differences between glacial and modern ocean in how much nitrate (NO₃⁻) there was. There is no NO₃⁻ in this version of GENIE (just PO₄³⁻ and Fe), but an analogous change can be made to the phosphorous cycle.

For the nutrient-to-carbon ratio in organic matter, the relevant parameter is:

```
bg_par_bio_red_POP_POC=106.0
```

To change the default value (106.0), add a new line at the end of the *user-config* file specifying the value you want. A larger number means that PO₄ is being utilized more efficiently and more organic matter is being produced for the same nutrient consumption. If you would like to test the effect of adding more PO₄ to the (glacial) ocean, add:

```
bg_ocn_dinit_8=1.0E-6
```

which will add 1 μmol kg⁻¹ of PO₄ uniformly to the ocean. (A larger/smaller number will obviously increase the glacial nutrient inventory by more/less.) Note that adjusting the ocean PO₄ inventory should only be done once (and not accidentally in each successive experiment!).

You'll be seeing similar parameters to this later, so it is just worth mentioned in passing what it is for: it is so that you can adjust the inventory (concentration) of any tracer in the ocean compared to a *re-start*. Otherwise, the only ways to adjust the ocean inventory are to

start from scratch ('cold', no *re-start*) with a different initial value, or create a *forcing* of the ocean. This single parameter is much simpler, but only changes things uniformly throughout the ocean. Units are mol kg⁻¹ (except for temperature and salinity).

[*Changing the 'Redfield' ocean plankton might be difficult ... but not impossible, although we are presumably talking releases of genetically modified organisms to the entire ocean and hence there are obviously some severe ethical concerns. However, adding macro nutrients such as PO₄ (more often, NO₃ is talked about) may be more feasible.*]

- **CaCO₃:POC rain ratio.** Kicked off by a classic 1994 Nature paper by Archer and Maier-Reimer (see: *Kohfeld and Ridgwell* [2009]), one powerful means of changing atmospheric CO₂ that has been proposed involves changes in the export ratio between CaCO₃ (shells) and POC (particulate organic matter). Such a change in ratio could come about through a variety of ways (e.g., via the 'silica leakage hypothesis' (see: *Kohfeld and Ridgwell* [2009]) and also through the direct effect of Fe on diatom physiology (see *Watson et al.* [2000] in Nature and also Supplemental Information). There are also ideas about an opposite ocean acidification effect, whereby the less acidic glacial (compared to modern) ocean led to increased calcification and CaCO₃ export. Note that this response (higher saturation == great calcification) is encoded into your model configuration – see *Ridgwell et al.* [2007b]. In GENIE, the CaCO₃:POC rain ratio is controlled (technically: scaled) by the parameter: `bg_par_bio_red_POC_CaCO3=0.04`

The pattern of CaCO₃:POC rain ratio is not uniform across the ocean (why? (see: *Ridgwell et al.* [2007, 2009]), and its pattern can be viewed in the (2D BIOGEM) netCDF variable: `misc_sur_rCaCO3toPOC`.

[*Note that it is unlikely that there is any parallel in a geoengineering context to this process.*]

- **Global weathering rate.** Refer to *Ridgwell and Zeebe* [2005] for the role of weathering. Also to *Kohfeld and Ridgwell* [2009] for some references to the changes in weathering that might have taken place between glacial and interglacial. Weathering is also highly relevant to some of the proposals for geoengineering ocean chemistry.

[However ... we are not going to explore this in the Lab itself. (There is nothing though to stop you exploring this in the assessed project.)]

Note that some of the side effects of concern in a geoengineering context include global ocean (export) productivity – i.e. as it relates to higher trophic levels such as fish (and hence fisheries). Global biological export is summarized in the text files with the name of the form:

`biogem_year_xxxx_yyy_diag_GLOBAL_SNAP.res`
with one file created and saved for each time-slice.

Also: depletion of oxygen in the ocean interior is an oft-cited concern in the context of manipulating the strength of the biological pump in the ocean. Easiest is to view vertical slices through the ocean, although horizontal slices at specific, relatively shallow depths, may be equally useful. Basically: you are looking for how the extent of dysoxia (low oxygenation) conditions spread, or even the onset of widespread anoxia (no dissolved oxygen). Both conditions are unfavourable (and the latter fatal) to animal life as well as having other biogeochemical implications.

- 11.3 Finally: explore how modifications to the ocean biological pump affects the patterns and magnitude of ocean acidification. To do this: firstly you will need a 'control' experiment – one with a prescribed release of CO₂ to the atmosphere but without any of the biological pump parameters having been changed (i.e. they stay at their spin-up, default values). This, in turn, requires that you specify a release of CO₂ to the atmosphere. The example *user-config* file `exp15_modernlores` specifies a fossil fuel CO₂ forcing (in addition to dust to the ocean surface) and can be modified and/or scaled in the *user-config* as per in the previous Lab. For the purpose of this Lab, it is not worth worrying about historical transients and 'realistic' SRES scenarios (but you could approximate both relatively simply with a few well chosen time-points and values in the forcing).