

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

IV: Consequences of fossil fuel CO₂ release and 'ocean acidification'

Relevant reading (and references therein):

Kleypas, J.A., Feely, R.A., Fabry, V.J., Langdon, C., Sabine C.L. and Robbins, L.L. (2006). Impacts of ocean acidification on coral reefs and other marine calcifiers: a guide for future research. Report of a workshop held 18–20 April 2005, St Petersburg, FL, sponsored by NSF, NOAA, and the US Geological Survey, 1-88.

www.ucar.edu/communications/Final_acidification.pdf

Orr, J.C., K. Caldeira, V. Fabry, J.-P. Gattuso, P. Haugan, P. Lehodey, S. Pantoja, H.-O. Pörtner, U. Riebesell, T. Trull, M. Hood, E. Urban, and W. Broadgate (2009) Research Priorities for Ocean Acidification, report from the Second Symposium on the Ocean in a High-CO₂ World, Monaco, October 6-9, 2008, convened by SCOR, UNESCO-IOC, IAEA, and IGBP, 25 pp.

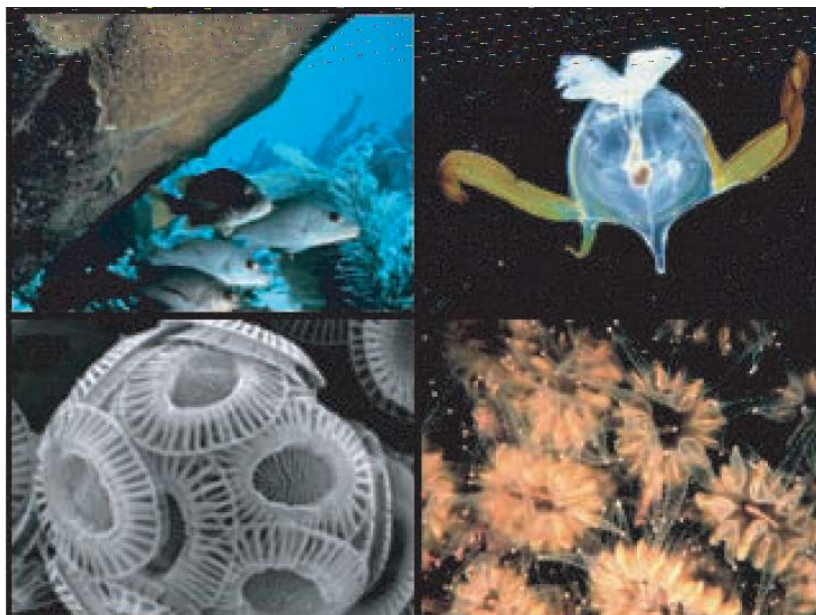
<http://ioc3.unesco.org/oanet/index.html>

Royal Society (2005) Ocean acidification due to increasing atmospheric carbon dioxide. Policy document 12/05 Royal Society, London.

<http://royalsociety.org/WorkArea/DownloadAsset.aspx?id=5709>

Turley, C., Findlay, H. S., Mangi, S., Ridgwell, A. and Schimdt, D. N., CO₂ and ocean acidification in Marine Climate Change Ecosystem Linkages Report Card 2009. (Eds. Baxter JM, Buckley PJ and Frost MT), Online science reviews, 25pp (2009).

<http://www.mccip.org.uk/elr/acidification/>



10. Exploring the consequences of fossil fuel CO₂ emissions

10.0 For the next experiment(s) you can chuck CO₂ into the atmosphere, just for the hell of it. As much as you want! Apparently, humans are actually doing this now. Imagine that!

The *user-config* for cGENIE, `exp8_co2emissions` is provided and configured with climate being responsive to CO₂ (i.e., it takes account of CO₂-climate feedbacks):

```
# set CO2-climate feedback  
ea_36=y
```

as well as having a rate of calcification by plankton at the surface ocean that is responsive to ocean acidification and saturation state (i.e., it takes into account CO₂-calcification feedbacks, which will additionally interact with climate – see *Ridgwell et al.* [2007b]). Anything could happen!!!

In the *user-config*, a release of CO₂ to the atmosphere is prescribed, which by default is set for 1000 PgC over an interval of a single year. (Releasing CO₂ just over a single year is obviously rather unrealistic, but represents a useful idealized experiment for assessing the time-scale(s) of fossil fuel CO₂ uptake by the ocean.) Additional netCDF output has also been prescribed (`bg_par_data_save_level=10`).

Because the *base-config* (`cgenie.eb_go_gs_ac_bg.worjh2.BASE`) has changed yet again(!) (carbon cycle tracers have now been added), you will first need to do a `make cleanall`.

Also: the model code has been adjusted very slightly and you'll need to again update your installation of the model. Simply change (`cd`) to the `cgenie` directory and type `svn update` as before. (Remembering to change directory back to `genie-main` before trying to run the model.)

10.1 Run the experiment for e.g., 10 (or more) years, starting from the *re-start* used previously, i.e.,:

```
$ ./runmuffin.sh cgenie.eb_go_gs_ac_bg.worjh2.BASE LABS  
exp8_CO2emissions 10 EXAMPLE.worjh2.Caoetal2009.SPIN
```

and view the run-time output, particularly atmospheric CO₂ (which decays away after the first year as fossil fuel CO₂ is progressively taken up by the ocean), ocean surface temperature (SST), sea-ice extent, and Atlantic Meridional Overturning ('AMO') strength (and/or other variables). Viewing the time-series results file `biogem_series_fexport_CaCO3.res` will show how global carbonate production responds to the ensuing ocean acidification, which itself is recorded in the file: `biogem_series_misc_surpH.res` for mean global surface pH, or `biogem_series_carb_sur_ohm_cal.res` for surface saturation with respect to calcite, with a variety of other carbonate parameters also outputted. The calcification response is encoded in the model and described in *Ridgwell et al.* [2007a,b] (see: <http://pubs.seao2.org>) and may or may not reflect the real World.

In the 3-D netCDF time-slice file, ocean pH is a particularly relevant field to consider together with calcite and aragonite saturation – note that ocean surface waters in which aragonite becomes under-saturated ($\Omega < 1.0$) is regarded as a critical threshold for organisms making aragonite shells and skeletons and spells TROUBLE for some poor calcifying marine organism somewhere. Temperature is also highly relevant to marine ecosystems under future global change as well as sea-ice extent.

In the 2-D netCDF time-slice file you are given water column integrals of dissolved things (e.g., DIC – `ocn_DIC_int`) (see: *Sabine et al.* [2004]; *Science* **305**). Also saved is the benthic (bottom water) conditions of ocean properties and carbonate chemistry. This is of particular relevance in assessing the changes in environmental conditions affecting cold-water (deep water) corals.

You might try creating difference maps in Panoply to assess the geographical characteristics of ocean acidification impacts. Ideally, one would run a parallel experiment, identical except for zero CO₂ release being specified, to act as a 'control' for the calculation of the differences. A difference map for the water-column integral of DIC (2D netCDF file), for instance, reveals where fossil fuel CO₂ is preferentially taken up by the ocean.

10.2 You can easily modify the experimental design to release more/less CO₂ very much as you did for the red dye tracer. In the *user-config* file, the lines:

```
bg_par_atm_force_scale_val_3=1000.0
bg_par_atm_force_scale_val_4=-27.0
```

scale the CO₂ flux and its δ¹³C isotopic signature, respectively. The scaling values are given to you for a CO₂ release of 1000 PgC yr⁻¹ (current emissions are about 8 PgC yr⁻¹) at -27‰ (typical of fossil fuel carbon). Altering the value assigned to *bg_par_atm_force_scale_val_3* in the *user-config* file gives immediate control over emissions rate.

You can also adjust the emissions to have a time-varying rate by editing the file:

```
biogem_force_flux_atm_pCO2_sig.dat
```

which can be found in the directory:

```
cgenie/genie_forcings/pyyyyz_FpCO2_Fp13CO2
```

The format of this file is:

```
-START-OF-DATA-
  0.0  8.3333e+013
  1.0  8.3333e+013
  1.0  0.0
999999.9  0.0
-END-OF-DATA-
```

and defines a total emission of 1000 PgC (8.333×10^{16} mol CO₂) over the first 1 year of the model experiment. (Year 999999.9 has no special meaning and is simply just way in the future ...)

Pause ... and note briefly how the final CO₂ flux is arrived at. GENIE calculates it by multiplying the value in the *forcing* file ($8.3333e+013$) by a modifying parameter in the *user config* file (1000.0). The total flux is hence: $8.333 \times 10^{13} \times 1000 = 8.333 \times 10^{16}$ mol CO₂.

Equally, we could have had 1.0 in the *forcing* file and $8.3333e+016$ as the value of *bg_par_atm_force_scale_val_3*. OR, the other way around.

The way you have been given as an example set up is simply for my own convenience in 'hiding' the units conversion in the *forcing* file and allowing me to simply enter a value in PgC yr⁻¹ in the *user-config* file. It is entirely up to you if you prefer to do things differently.

10.3 Between the start and end 'tags', the data is in 2 columns: the first contains a series of tie-points for defining the timing of changes in emissions, and the 2nd contains the flux information (units of mol yr⁻¹). At each time-step of the model the CO₂ flux is interpolated between these time points.

The purpose of:

```
0.0  8.3333e+013
1.0  8.3333e+013
1.0  0.0
```

is thus to effect a sharp turn-off of the flux at the end of first year. To extend the period of emissions – for example:

```
0.0  8.3333e+013
10.0  8.3333e+013
10.0  0.0
```

would give you uniform 1000 PgC yr⁻¹ pulse lasting 10 years. In contrast;

```
0.0  0.0
10.0  8.3333e+013
```

would result in a linear ramp, zero at the start of year 0.0 to $8.3333e+016$ mol yr⁻¹ at year 10.0 (a total CO₂ emission of $1000 \times 10 \times 0.5 = 5000$ PgC over 10 years).

It is also possible to provide a simple scaling of the (default) unit duration of the pulse in the *user-config* file by adding the lines:

```
bg_par_atm_force_scale_time_3=10.0
bg_par_atm_force_scale_time_4=10.0
```

which would scale the duration of the pulse (of CO₂ and its isotopic signature) by a factor to 10, i.e., to 10 years. (Remember, that without changing the default emissions rate, you will end up with 10,000 PgC total CO₂ emitted ... !)

- 10.4 By editing (and saving) the flux (and/or timing information) you can exert fine control on the CO₂ emissions trajectory and total fossil fuel burn. Explore different CO₂ release assumptions and note their impact on climate and ocean biogeochemistry. Much more realistic and appropriate to our current global experimenting is a lower rate (order of 10 or 20 PgC yr⁻¹) released over a longer interval (order 100 years). Because the experiments are getting longer to run in real time ... remember to make appropriate use of the cluster queuing facility.

Possible questions you might have (or be persuaded to have) might include:

How much CO₂ emissions does it take to significantly ‘collapse’ the AMOC and over what time-scale? (Or alternatively: what is the atmospheric pCO₂ threshold for collapse?)

What is the maximum total CO₂ release that can be made without inducing aragonite under-saturation at the ocean surface anywhere? How important is the time-scale (or ‘shape’) of the emissions trajectory in determining this? For total emissions above this: where in the ocean does the surface first become under-saturated? How large would the emissions have to be in order to induce under-saturation at the surface in the tropics (home to tropical corals and socio-economically important reef systems). These are questions that are addressed with simple CO₂ release experiments in ocean carbon cycle models and everyone seems to get a GRL paper out of it each and every time! No names mentioned ...

Also: how important are CO₂-climate feedbacks in amplifying or diminishing future climate and ocean carbonate chemistry changes? You can investigate this by contrasting an experiment made including CO₂-climate feedback with one made without (CO₂-climate feedback can be turned off by the setting: `ea_36=n`).

- 10.5 Historical and future (SRES) emissions scenarios can also be prescribed explicitly. A historical emissions *forcing* (technically: a prescribed concentration profile of pCO₂ and other anthropogenic gases) can be specified by adding/substituting the following lines:

```
bg_ctrl_force_oldformat=.false.  
bg_par_forcing_name='pyyyyz_historical2010'
```

Here, no additional scaling is needed because the *forcing* specification directly follows observed atmospheric concentration profiles.

An additional line is needed in the *user-config* because historical emissions start in the 1700s (for which a nominal date of 1765 is often used) rather than year zero. For example, to start from year 1700, the start year parameter must be set:

```
bg_par_misc_t_start=1700.0
```

Because the start year has changed, it is convenient to specify save points that are consistent with the historical period, e.g.:

```
bg_par_infile_slice_name='save_timeslice_historical.dat'  
bg_par_infile_sig_name='save_sig_historical.dat'
```

A suitable experiment would then be one run for 310 years so that it reaches year 2010 (having started from year 1700):

```
$ ./runmuffin.sh cgenie.eb_go_gs_ac_bg.worjh2.BASE LABS exp9_historical  
310 EXAMPLE.worjh2.Caoetal2009.SPIN
```

WARNING! Ignore the ‘WARNING’s at the start – these are simply telling you that more *tracer forcings* have been specified than you have selected tracers for in the *base-config* (`cgenie.eb_go_gs_ac_bg.worjh2.BASE`). (A different *base-config* with additional selected tracers could have been specified to make use of other historical changes in atmospheric composition, such as of radiocarbon (¹⁴C) and CFCs.) Also: from year 1700 onwards, changes in atmospheric CO₂ only rise very slowly initially. Don’t expect to see anything happen in 10 seconds flat! (Or be 20% cooler.)

*** Because a 310 year experiment is going to be particularly tedious to wait for, with nothing much happening for the first ~150 years because relatively few people and countries in the 1800s could be bothered to burn much more than a little local coal, you could maybe start your experiment at year 1850. Note that you would then need to change the value of `bg_par_misc_t_start`. You will also need to specify a shorter experiment duration. However, in doing this you will not have a convenient start-of-run time-slice saved for you, requiring you either to edit the file `save_timeslice_historical.dat` (in `genie-biogem/data/input`) or run a control experiment (one identical except with no CO₂ emissions) to provide you with an unperturbed baseline start of the system. (Ideally, you would run a control experiment anyway.)

- 10.6 Given that there is observationally-based information on the distribution of anthropogenic CO₂ taken up by the ocean (e.g. *Sabine et al.* [2004]) and having run a historical transient experiment with the model driven by observed increases in atmospheric *p*CO₂, you are in a position to critically evaluate the model's ability (or lack of) to represent the future-critical process of oceanic fossil fuel CO₂ uptake and transport by large scale ocean circulation.

In the 2D netCDF output, there is a variable for the water column integrated inventory of DIC – equivalent to the Sabine map except you will need to subtract the preindustrial background of DIC first, i.e. to create a DIC anomaly map representing only the added fossil fuel CO₂ component of ocean DIC. The data in the Sabine paper clusters around 1994. A time-slice centered on this year (1994.5) has been configured in the model exactly for this purpose. Your baseline state can either be from prior to CO₂ emissions commencing at any significant rate (e.g. 1750.5) or (better), from a control experiment. Note that similar comparisons could be (and are regularly) made with other tracers such as CFCs, which provide additional insights into the patterns and time-scales of trace gas uptake and ocean circulation. (See: *Cao et al.* [2009])

Observational data, re-gridded to the cGENIE grid and in netCDF format can be downloaded from the 'usual place' (<http://www.seao2.org/mucgenie.html>) under 'Observations on cGENIE grid'. You could for instance, compare horizontal or vertical slices (3D netCDF) and create difference (anomaly) maps. Somewhat more representative of the entire ocean is to compare (or calculate difference maps) of zonal average profiles. (Unfortunately, the observations are not in the form of water column integrals and hence you cannot create difference maps of model – Sabine data. You can, however, if you use the 3D BIOGEM MATLAB plotting scripts (`genie-matlab`).

Examples of MATLAB plotting of the model vs. observed anthropogenic anomaly are show in the Figure.

Interesting (to me at least) and of paleo relevance is the $\delta^{13}\text{C}$ anomaly in the ocean. Fossil fuel CO₂ is isotopically much lighter than the modern atmosphere and ocean, and its gradual penetration into the ocean interior leaves a distinct geochemical signature.

- 10.7 Finally, and the closest to be interesting of all: rather than applying highly idealized pulses (or other artificial shapes) of CO₂ emissions, IPCC SRES emissions scenarios can be used to make future projections by running on from the end of the historical transient. An example forcing of this sort is provided and can be selected by changing the name of the forcing selection parameter (`bg_par_forcing_name`) to:

```
pyyyyz_FpCO2_Fp13CO2_A2_02180PgC
```

which gives you the IPCC 'A2' scenario, which has been extended beyond year 20100 in this case to give a total cumulative fossil fuel burn of 2018 PgC (and used in *Ridgwell and Schmidt* [2010]).

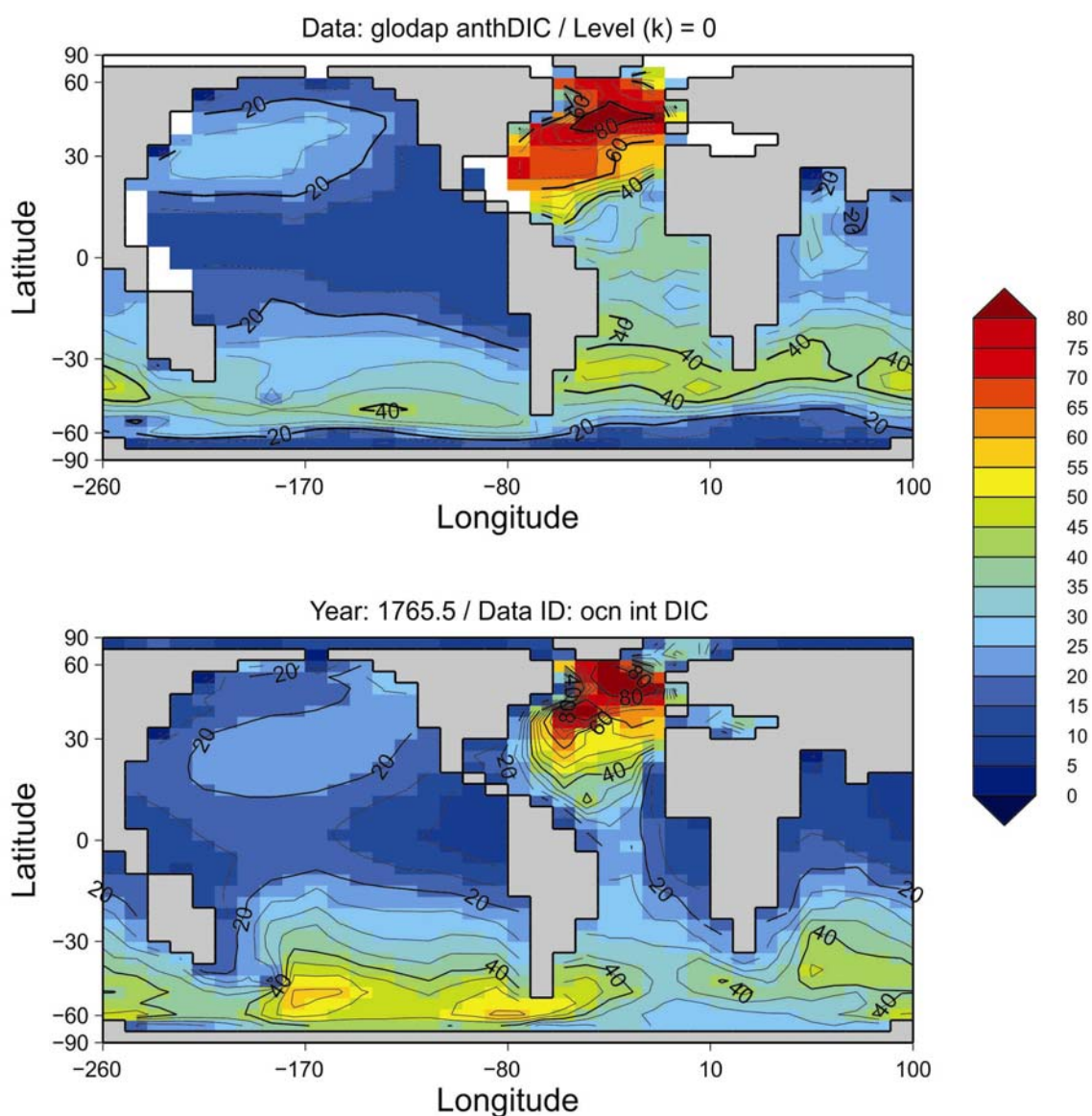
As this forcing has units of PgC yr⁻¹, you will need to add a scaling parameter to turn into mol yr⁻¹:

```
bg_par_atm_force_scale_val_3=8.3333e+013
```

You can easily replace the details of the emissions with other SRES scenarios – simply find the year vs. emissions rate information from the interweb (e.g.

http://sres.ciesin.columbia.edu/final_data.html) and edit (or copy-and-paste) the flux values for each decade in `biogem_force_flux_atm_pCO2_sig.dat` (the mode will then automatically interpolate to give a continuous change in emissions). Now you are able to make a rather more realistic/plausible assessment of when and where certain potential ecological impacts (vai assumed ocean chemistry criteria) might occur.

You may want to re-adjust the saving criteria commensurate for an into-the-future experiment. For instance, provided for you are the time-slice and time-series save definitions (for setting the `bg_par_infile_slice_name` and `bg_par_infile_sig_name` parameter values):
`save_timeslice_future.dat` and `save_sig_future.dat`



Observed (top) vs. Model (bottom) anthropogenic CO₂ inventories.

Data and model water column integrals in units of mol CO₂ m⁻² and are nominally with respect to year 1994.