The *USSP2011* Hitchhikers Guide to the Black Arts (of Earth system modelling)

IV: Consequences of fossil fuel CO_2 release and 'ocean acidification'

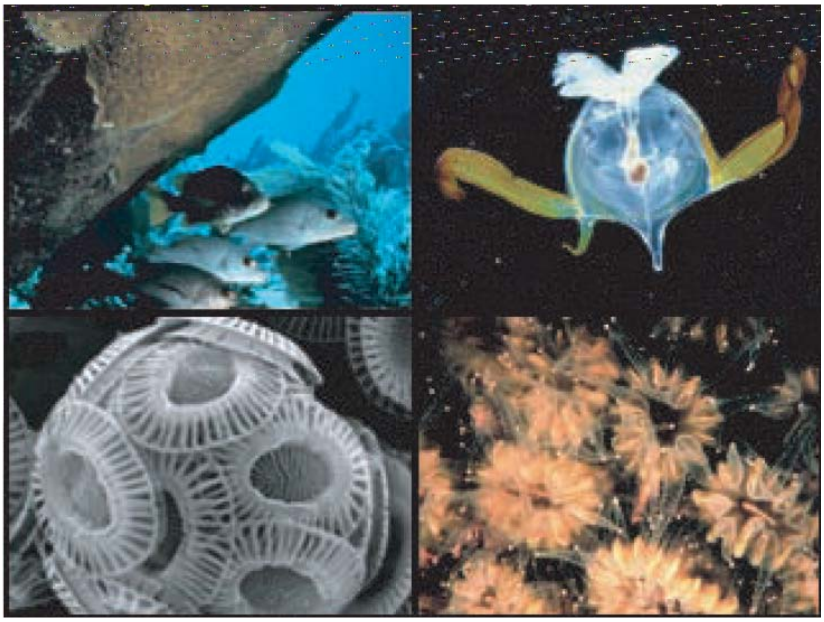
Relevant reading (and references therein):

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 CO_2 emissions

10.0 For the next experiment(s) you can chuck CO_2 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 *c*GENIE, `exp8_co2emissions` is provided and configured with climate being responsive to CO_2 (i.e., it takes account of CO_2-climate feedbacks):

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

as well as a rate of calcification in the surface ocean that is responsive to *p*H (i.e., it takes into account CO_2-calcification feedbacks, which will additionally interact with climate – see *Ridgwell et al.* [2007b]). Anything could happen!!!

In the *user-config*, a release of CO_2 to the atmosphere is prescribed, which by default is set for 1000 PgC over an interval of a single year. (Releasing CO_2 just over a single year is obviously rather unrealistic, but represents a useful idealized experiment for assessing the time-scale(s) of fossil fuel CO_2 uptake by the ocean.) Additional results output has also been prescribed:

```
bg_ctrl_data_save_slice_ocnatm=.true.
bg_ctrl_data_save_slice_fairsea=.true.
bg_ctrl_data_save_slice_carb=.true.
bg_ctrl_data_save_slice_ocnsed=.true.
bg_ctrl_data_save_sig_carb_sur=.true.
bg_ctrl_data_save_slice_misc=.true.
bg_ctrl_data_save_derived=.true.
```

Because the *base-config* (`cgenie_eb_go_gs_ac_bg.worjh2.BASE`) has changed compared to the previous exercise (carbon cycle tracers have been added), you will need to first do a `make cleanall`.

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

```
$ ./runcgenie.sh cgenie_eb_go_gs_ac_bg.worjh2.BASE LABS
 exp8_CO2emissions 10 exp0_modern16_SPINUP
```

and view the run-time output, particularly atmospheric CO_2, ocean surface temperature (SST), sea-ice extent, and Atlantic Meridional Overturning (‘`AMO`’) strength. 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`. This response is encoded in the model and described in *Ridgwell et al.* [2007a,b] (see: http://pubs.seao2.org).

Note how atmospheric CO_2 starts to decay away after the first year as fossil fuel CO_2 is progressively taken up by the ocean.

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. (Also: temperature is particularly relevant to future global change as well as sea-ice extent (and whatever else takes your fancy …).)

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 would be particularly relevant for assessing the changes in environmental conditions affecting old-water corals.

Also 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 CO_2 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 CO_2 is preferentially taken up by the ocean.

10.2 You can easily modify the experimental design to release more/less CO_2 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 CO_2 flux and its $\delta^{13}C$ isotopic signature, respectively. The scaling values are given to you for a CO_2 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 CO_2) over the first 1 year of the model experiment. (Year 999999.9 has no special meaning and is simply just a number way in the future …)

Pause … and note briefly how the final CO_2 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: $8.333\times10^{13} \times 1000 = 8.333\times10^{16}$ mol CO_2.

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 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 (in units of mol yr^{-1}). Note that at each time-step of the model the CO_2 flux is interpolated between the time points.

The purpose of the:

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

bit 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 1000 PgC yr^{-1} over 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 CO_2 emission of 1000×10×0.5 = 5000 PgC over 10 years).

It is also possible to provide a simple scaling of the (by 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 CO_2 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 CO_2 emitted … !)

10.4 By editing (and saving) the flux (and/or timing information) you can exert fine control on the CO_2 emissions trajectory and total fossil fuel burn. For instance, the IPCC 'SRES' scenarios of possible future CO_2 emissions can be reconstructed and their implications tested in GENIE.

Play with different CO_2 releases 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 of order 100 years.

How much CO_2 emissions does it take to significantly 'collapse' the AMOC and over what time-scale? (Or alternatively: what is the atmospheric pCO_2 threshold for collapse?)

What is the maximum total CO_2 release that can be made without inducing aragonite saturation anywhere? How important is the time-scale (or 'shape') of the emissions trajectory? For total emissions above this: where in the ocean does the surface first become under-saturated? (These are questions that are addressed with simple CO_2 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 …)

10.5 Historical and future (SRES) emissions scenarios can also be prescribed explicitly. A historical emissions *forcing* (technically: a prescribed concentration profile of pCO_2 and other anthropogenic gases) can be specified by adding the following forcing lines (maybe delete the original ones first):

```
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 ca. 1765 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'
```

This experiment would be run for 310 years in order to reach year 2010 (from 1700):

```
$ ./runcgenie.sh cgenie_eb_go_gs_ac_bg.worjh2.BASE LABS exp9_historical
 310 exp0_modern16_SPINUP
```

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 (^{14}C) and CFCs.)

Also: from year 1700 onwards, changes in atmospheric CO_2 only rise very s l o w l y initially. Don't expect to see anything happen in 10 seconds flat!

10.6 Finally, note that the previous experiment could be used as a *restart* for emissions from year 2010 onwards. (You would need to change the start year of course.) (hint: *user-config* `exp10_future`)