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

`Lesson #3:` 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/
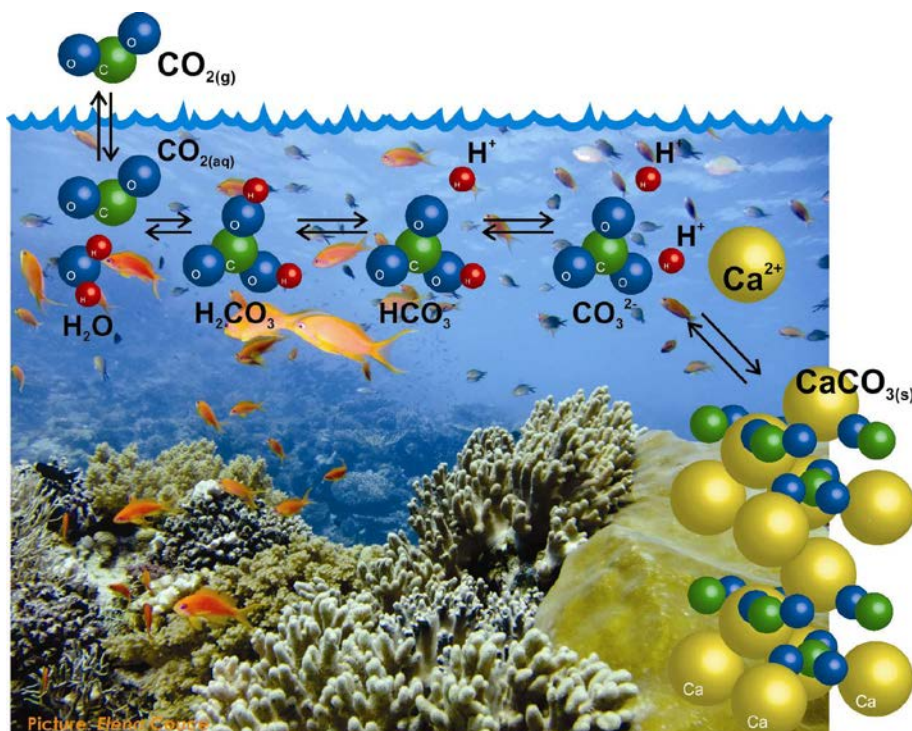
0. Readme

0.0   You will need to download a new *restart* file prior to embarking on the experiments. This pre-industrial spin-up includes a basic ocean (-atmosphere) carbon cycle plus various diagnostic anthropogenic tracers, following *Cao et al.* [2009].

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

`$` `wget http://www.seao2.info/cgenie/labs/AWI.2017/LAB_3.SPIN.tar.gz`

Extract the contents of this archive by typing:

`$` `tar xfzv LAB_3.SPIN.tar.gz`

(change directory back to `genie-main` to run the model)

1. Exploring the consequences of fossil fuel CO_2 emissions

1.0   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, `LAB_3.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 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 CO_2-calcification feedbacks, which will additionally interact with climate – see *Ridgwell et al.* [2007b, 2009] from http://www.seao2.info/pubs.html). Anything could happen!!!

In this *user-config* file, a release of CO_2 to the atmosphere is prescribed, which by default is set for just 1 PgC over an interval of a single year. (Releasing CO_2 just over a single year is obviously rather unrealistic and many impacts will decay rapidly away, but represents a useful idealized experiment for assessing the time-scale(s) of fossil fuel CO_2 uptake by the ocean.) Additional netCDF output has also been prescribed (`bg_par_data_save_level=10`) so that more information relevant to assessing ocean acidification is saved.

1.1   Run the experiment for e.g., 20 (or more if you like) years, starting from the pre-industrial *re-start* experiment `LAB_3.SPIN`, i.e.:

```
$ ./runmuffin.sh cgenie.eb_go_gs_ac_bg.worjh2.BASE LABS
 LAB_3.CO2emissions 20 LAB_3.SPIN
```

As for what model results variables to consider … think about the climate change and ocean acidification literature and which environmental properties are considered either critical for ecosystems or are simply helpful and illustrative. Refer to the Ocean acidification output supplement (S1) for a summary of some of the key ocean acidification variables saved by the model.

In the 3-D netCDF time-slice file remember, for instance, 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.) Note that 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.

For climate change ... the variables of particular interest should be obvious. Remember that there are both time-series outputs, as well as special 2D and 3D fields which might be more helpful for relating impacts to specific ecosystems.

1.2   You can easily modify the experimental design to release more/less CO_2 very much as you did for the red dye tracer. In the *user-config* file, the line:

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

scales the CO_2 flux given in the forcing file

```
biogem_force_flux_atm_pCO2_sig.dat
```

which can be found in the directory:

```
cgenie.muffin/genie_forcings/pyyyyz.FpCO2_Fp13CO2
```

The format of this file is:

```
-START-OF-DATA-
      0.0   1.0
      1.0   1.0
      1.0   0.0
 999999.9   0.0
-END-OF-DATA-
```

3

and defines an emission of 1 mol C per year over the first 1 year of the model experiment (between year `0.0` and `1.0`), but which in the example *user-config* is then scaled by a value of 8.333×10^{13} (by the parameter `bg_par_atm_force_scale_val_3`) to give a total of 1 PgC yr^{-1}. (Year 999999.9 has no special meaning and is simply just way in the future …)

Pause … and note briefly how the final CO_2 flux is arrived at. *c*GENIE calculates it by multiplying the value in the *forcing* file (`1.0`) by a modifying parameter in the *user config* file (`8.3333e+13`). The total flux is hence: $1.0 \times 8.333 \times 10^{13} = 8.333 \times 10^{13}$ mol CO_2 yr^{-1}. If you set both values as `1.0`, you'd get very little carbon released (a single mole!). If you screw up and multiply `8.3333e+013` and `8.3333e+013` as the total flux, you'll soon know it as you cook the Earth … But it does not matter which parameter has value `1.0` and which scales the units (`8.3333e+013`). For now, it is simply more convenient to be able to edit the *forcing* file with simple numbers (and leave the units conversion in the *user config* file).

Together, the scaling and forcing value gives a CO_2 release of 1 PgC yr^{-1} for just a single year compared to current emissions are about 10 PgC yr^{-1}. So, do not expect anything exciting to happen at this point.

(The parameter: `bg_par_atm_force_scale_val_4=-27.0` specifies the carbon isotopic composition of fossil fuel carbon and can be ignored.)

1.3 Because 'accidents can happen' and the global environmental changes induced by the massive fossil fuel CO_2 release can obscure mistakes made in the experiment configuration (parameter values) and/or the *re-start* used, you are strongly advised to first (or in parallel, as a job submitted to the cluster – refer to Lesson Zero to remind yourself of the commend line syntax needed for this) set a control experiment going:

```
$ ./runmuffin.sh cgenie.eb_go_gs_ac_bg.worjh2.BASE LABS
 LAB_3.CONTROL 20 LAB_3.SPIN
```

Here – the *user-config* defining the control experiment (`LAB_3.CONTROL`) is identical to that for the actual experiment itself (`LAB_3.CO2emissions`) with the exception of the scaling of the CO_2 emissions that have been set to zero. (It is left completely to you to create the experiment configuration file `LAB_3.CONTROL`.)

If everything is OK, atmospheric *p*CO_2 (and climate) should be stable and there should be little (or no) drift in any of the output variables (because the spin-up should have been run to an equilibrium state and you have not changed anything in the control experiment, right?).

It is good practice (i.e. <u>do it!</u>) to always run a control experiment for each different type of experiments – e.g. ideally run one control experiment for each set of CO_2 emissions experiments.

1.4 OK. You might want to run something a little more exciting now. For instance, rather than

```
-START-OF-DATA-
      0.0  1.0
      1.0  1.0
      1.0  0.0
 999999.9  0.0
-END-OF-DATA-
```

you might have:

```
-START-OF-DATA-
      0.0  1000.0
      1.0  1000.0
      1.0     0.0
 999999.9     0.0
-END-OF-DATA-
```

So now a total of 1000 PgC over a single year. Now you should see some policy-relevant impacts occur :o)

1.5 You can control the shape of the emissions profile as well as it magnitude. Between the start and end 'tags' in the text file, the data is arranged into 2 columns: the first contains a series of tie-points for defining the timing of changes in emissions, and the 2nd column contains flux information (units

of PgC yr^{-1} when scaled by the parameter parameter `bg_par_atm_force_scale_val_3` in the *user-config*). At each time-step of the model the CO_2 flux is interpolated between these time points. The purpose of:

```
0.0  1.0
1.0  1.0
1.0  0.0
```

then specifies a uniform flux of `1.0` (scaled to PgC yr^{-1}) over the first full year of the model run, followed by a sharp turn-off to zero flux at the end of first year (and remaining zero thereafter). To extend the period of emissions – for example:

```
0.0  1.0
10.0  1.0
10.0  0.0
```

would result in a uniform flux lasting 10 years (i.e. once scaled by the parameter in the *user-config* – 1 PgC yr^{-1} over 10 years – 10 PgC total emissions). In contrast;

```
0.0  0.0
10.0  1.0
```

would result in a linear ramp, starting from zero at the start of year 0.0 to 1.0 PgC yr^{-1} at year 10.0 (a total CO_2 emission of $1 \times 10 \times 0.5 = 5$ PgC over 10 years).

1.6   Historical and future (SRES) emissions scenarios can also be prescribed explicitly. A historical emissions *forcing* (technically: a prescribed <u>concentration profile</u> of $p$$CO_2$ and other anthropogenic gases) can be specified by adding/substituting the following lines to the *user-config*:

`bg_par_forcing_name='worjh2.historical2010'`

Now, no additional scaling is needed because the *forcing* specification directly follows the observed change in atmospheric concentration with time (in units of atm CO_2) and the line containing the scaling parameter:

`bg_par_atm_force_scale_time_3=1.0`

should be deleted (or commented out with a `#` at the start of the line).

An additional line is needed in the *user-config* because the historical $p$$CO_2$ transient starts in the 1700s (for which a nominal date of 1765 is often used) rather than year zero. For example, to start from year 1765, the start year parameter must be set:

`bg_par_misc_t_start=1765.0`

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_historicalfuture.dat'`
`bg_par_infile_sig_name='save_timeseries_historicalfuture.dat'`

A *user-config* with these changes is provided for your convenience (or to double-check you were following it all) – `LAB_3.historical`. A suitable experiment would then be one run for 245 years so that it reaches year 2010 (having started from year 1765):

```
$ ./runmuffin.sh cgenie.eb_go_gs_ac_bg.worjh2.BASE LABS
 LAB_3.historical 245 LAB_3.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 (^{14}C) and CFCs.) Also: from year 1765 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 because relatively few people and countries in the 1800s could be bothered to burn much more than a little local coal. You could potentially start your experiment at year 1850, changing the value of `bg_par_misc_t_start` and specifying shorter experiment duration if you are desperate for the End of the World to come.

Don't forget: you could submit this experiment to the cluster and do more Section 1.4/1.5 'playing'.

1.7 Given that there is observationally-based information on the distribution of anthropogenic CO_2 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 pCO_2, 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 CO_2 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 CO_2 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 CO_2 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 update 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/mycgenie.html) from the 'got data?' box on the left. 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 as per the Sabine paper … unless you are MATLAB-friendly and you use the 3D BIOGEM MATLAB plotting scripts (`genie-matlab`) whose use is somewhat described in the *c*GENIE user-manual. Examples of MATLAB plotting of the model vs. observed anthropogenic anomaly are shown in the Figure (note the use of plotting un-interpolated model grid data as colors but with an interpolated contour overlain to help guide the eye and pick out features).

1.8 Finally, and the closest to being slightly interesting: rather than applying highly idealized pulses of CO_2 emissions, IPCC SRES emissions scenarios can be used to make future projections with. 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:

`worjh2.FeMahowald2006.FpCO2_Fp13CO2_A2_02180PgC`

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

Again, as this *forcing* has units of PgC yr^{-1} in its time-series file, you will need to add a scaling parameter to the *user-config* file to turn units of PgC yr^{-1} into mol yr^{-1}, i.e.

`bg_par_atm_force_scale_val_3=8.3333e+013`

For complete 'realism' you will need to run this experiment starting from the end of the historical transient experiment (Section 1.6), e.g.

```
$ ./runmuffin.sh cgenie.eb_go_gs_ac_bg.worjh2.BASE LABS
 LAB_3.future 90 LAB_3.historical
```

and with the start from year now set to year 2010 (the end year of the historical transient):

`bg_par_misc_t_start=2010.0`

Note that the user-config `LAB_3.future` is not provided for you – create this (or a file named whatever you like) by copying e.g. `LAB_3.EXAMPLE` and making the parameter changes described above (forcing specification parameter, emissions scaling parameter, and start year parameter).

You can also 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 into the file `biogem_force_flux_atm_pCO2_sig.dat` in the *forcing* directory. *c*GENIE will then automatically interpolate between the decadal tie-points to give a continuous change in emissions. Now you are able to make a rather more realistic/plausible assessment of when and where potential ecological impacts (via assumed ocean chemistry criteria) might occur.
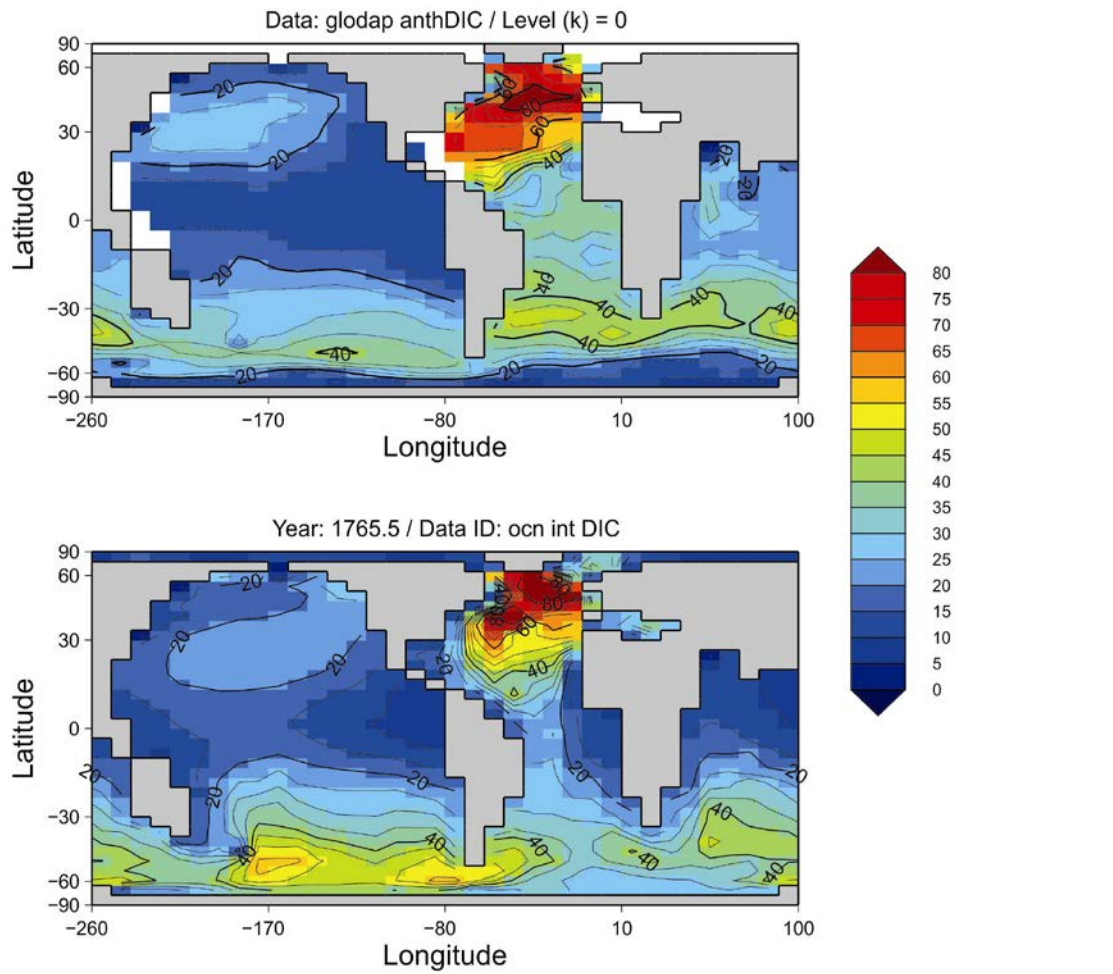
Observed (top) vs. Model (bottom) anthropogenic CO₂ inventories.

Data and model water column integrals in units of mol CO_2 m^{-2} and are nominally with respect to year 1994.

2. Further ideas

2.0 Assessing the importance of emissions rate

By editing the flux and/or timing information you can control the CO_2 emissions trajectory and total fossil fuel burn. Explore different CO_2 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) compared to the conceptual 1000 PgC near instantaneous pulse. Because the experiments are getting longer to run in real time … remember to make appropriate use of the cluster queuing facility – i.e. think about whether you want to sit around starting at the screen for 15 minutes waiting for a new line of numbers appear – if not: submit to the cluster queue. For instance, one might try and address the question: "For a given total release of CO_2, is it safer to burn it slower?" The answer is maybe not completely obvious, as burning carbon resources slower will result in a small global impact, but perhaps one that persists for longer. You could conceive of an ensemble (set) of model experiments, maybe one of 100 PgC yr^{-1} for 1 yr, one of 10 PgC yr^{-1} for 10 years, and one of 1 PgC yr^{-1} for 100 years, and run them all for e.g. 100 years. (As jobs submitted to the queue, all can be run simultaneously.) (Don't forget the control experiment!) But note that you should create 3 new *forcings* based on the original if you are editing the *forcing* and expecting to run different ones at the same time. Really, this is little from copying and renaming *user-config* files, except it involves entire directories in `genie-forcings`. Remember that the *forcing* is specified by the directory name assigned to `bg_par_forcing_name` (enclosed in `" "`).

2.1 Determining thresholds of environmental impact

There are various concerns about the impacts of continuing fossil fuel CO_2 emissions and a number of proposed climatic (e.g. the 2 degree C global warming limit often mentioned in policy documents) and ecological 'tipping points'. You can assess the maximum allowable CO2 emissions to remain within particular global environmental limits in the model. For example:

What is the maximum total CO_2 release that can be made without inducing aragonite under-saturation at the ocean surface anywhere (or any season – see Section 5.2.3 in the User Manual for seasonal time-slice data saving)**? How important is the time-scale of emissions 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 socio-economically important reef systems).** These are questions that can be 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!

How important are CO_2-cimate feedbacks in amplifying or diminishing future climate and ocean carbonate chemistry changes – e.g. is the same atmospheric *p*CO_2 value reached with and without climate feedback (and surface warming) – if not, why? You can investigate this by contrasting an experiment made including CO_2-climate feedback with one made without. The CO_2-climate feedback can be turned off by setting: **`ea_36=n`**.

Also: **How much CO_2 emission does it take to significantly 'collapse' the AMOC and over what time-scale? (Or alternatively: what is the atmospheric *p*CO_2 threshold for collapse?) If the AMOC weakens or collapses … why in the absence of a prescribed freshwater perturbation does this happen?** (Plotting appropriate ocean property anomalies between the CO_2 release experiment and a control experiment might help.)

Experiments could be hypothetical and consisting of CO_2 pulses or ramps (or exponentials) and run on directly from a pre-industrial spin-up, or more 'realistic' and run on from the end of a historical transient experiment (e.g. starting in year 2010).

S1. Ocean acidification output supplement

S1.0 Variables relevant to ocean acidification are saved in the 'usual' formats – *time-series* (`.res`) files, 3D netCDF, and also 2D netCDF *time-slice* files. The most relevant ones of interest are as follows with the more useful ones highlighted in **bold** (although this is not an exhaustive list of what might be relevant to look at …)

S1.1 *Time-series* files:

`biogem_series_misc_surpH.res` - mean ocean surface pH
(useful OA diagnostic that can be related to the literature)

`biogem_series_carb_sur_ohm_cal.res` - mean ocean surface carbonate saturation (calcite)
(useful OA diagnostic that can be related to the literature)

`biogem_series_carb_sur_ohm_arg.re`s - mean ocean surface carbonate saturation (aragonite)
(useful OA diagnostic that can be related to the literature)

`biogem_series_fexport_CaCO3.res` - global $CaCO_3$ export (from planktic calcifiers)
(indicator of impact of climate change and OA on planktic calcifiers, although see earlier caveats)

`biogem_series_fexport_POC.res` - global organic matter export (from all plankton)
(indicator of climate impacts on ocean circulation and hence nutrient supply and plankton export production)

And of course, time-series of *temperature* (e.g. mean surface, ocean or air temperature), Atlantic meridional overturning strength (AMOC), and sea-ice cover.

S1.2 3D netCDF *time-slice* file (`fields_biogem_3d.nc`):

`misc_pH` - ocean pH
(the patterns are not that eciting …)

`carb_ohm_cal` - carbonate saturation (calcite)
(relevant to the habitat of marine organisms producing calcite)

`carb_ohm_arg` - carbonate saturation (aragonite)
(relevant to the habitat of marine organisms producing aragonite)

`bio_fpart_CaCO3` - $CaCO_3$ export flux (from planktic calcifiers)
(spatial pattern of planktic carbonate export)

`bio_fpart_POC` - organic export flux (from all plankton)
(spatial pattern of planktic organic matter export)

And of course, *time-slices* of temperature and salinity, perhaps also dissolved oxygen (`ocn_O2`) that decreases in a warming ocean and also if the organic carbon flux increases.

S1.3 2D netCDF *time-slice* file (`fields_biogem_2d.nc`):

`ocn_int_DIC` - is the water-column integrated inventory of dissolved carbon (refer to hand-out)
(diagnostic of the pattern of CO_2 uptake by the ocean)

`misc_sur_rCaCO3toPOC` - is the ratio between $CaCO_3$ and POC export – i.e. comparatively, how much $CaCO_3$ is exported
(diagnostic of how $CaCO_3$ production changes relative to POC)

And of course, the overturning stream-function.