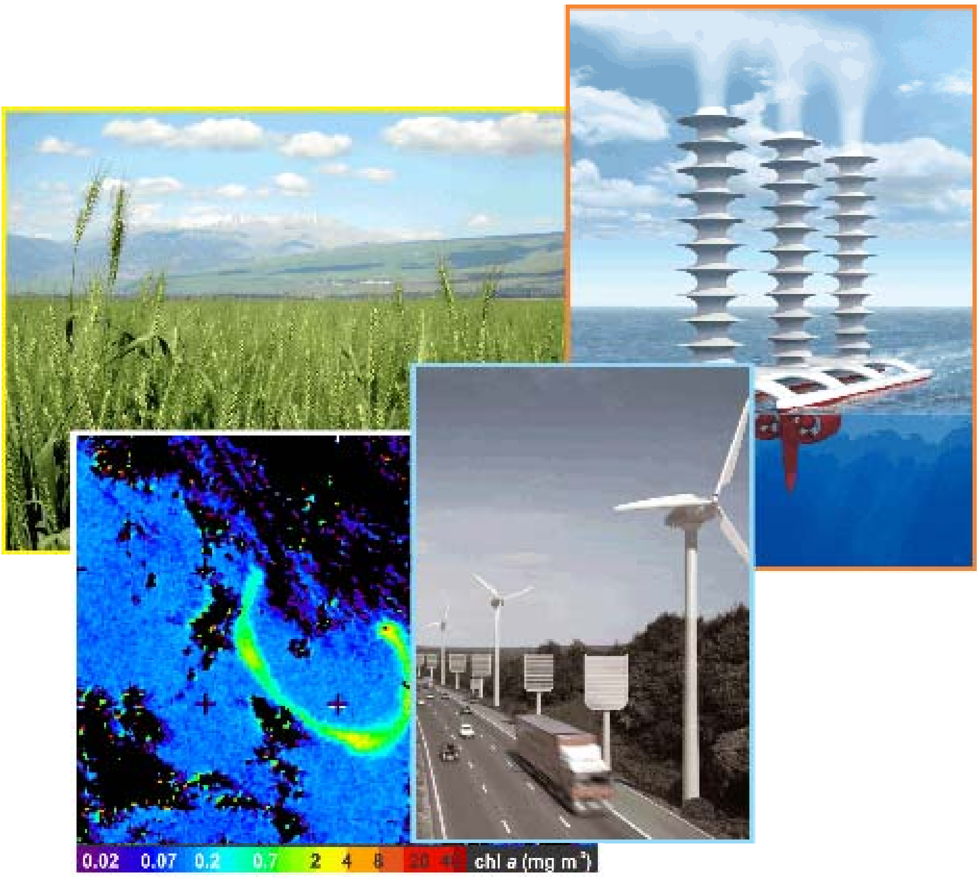
A Hitchhikers Guide to the Black Arts
(of Earth system modelling)
`PART #0101:` Engineering the carbon cycle



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/UoB.2013/EXAMPLE.worjh2.PO4Fe.HISTORICAL.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. Engineering the carbon cycle

1.0 In the following experiments you are going to be running future CO_2 emissions scenarios and explore whether certain ocean carbon geoengineering proposals are an effective means for reducing future ocean acidification and marine ecological impacts. You will require both a pre-industrial spin-up as well as a historical pCO_2 transient experiment (e.g. as per session **`#0100`**). of the ocean biological controls on atmospheric pCO_2 (and surface ocean geochemistry and ocean acidification).

1.1 A template 'A2' emissions *user-config*: `LAB.0101.GEO` is provided. This includes parameters for controlling 2 different possible ocean carbon geoengineering schemes, described below. By default, these are commented out (== ignored by the model) and only the *forcing* for the A2 emissions scenario (`worjh2_FeMahowald2006_FpCO2_Fp13CO2_A2_02180PgC`) with no geoengineering is set (parameter: `bg_par_forcing_name`). You might regard this as a control (reference) experiment for all the with-geoengineering experiments. To activate any particular geoengineering *forcing*: simply comment out the appropriate pair of lines (the first line being the *forcing* specification, and the second one the total flux *forcing* used in the geoengineering scheme). Remember that if you have multiple (un-commented-out) settings of a parameter (e.g. `bg_par_forcing_name`) the value specified in the last occurrence is the one that is applied.

The experiment needs to be run starting from the end of a historical transient experiment run to year 2010 (see: session #**`0100`**):

```
$ ./runmuffin.sh cgenie.eb_go_gs_ac_bg.worjh2.BASEFe LABS
 LAB.0101.GEO 90 EXAMPLE.worjh2.PO4Fe.HISTORICAL
```

1.2 The example geoengineering scenario is defined by a specific *forcing*, constituting a set of files in a uniquely named sub-directory within `genie-forcings`. This is:

- `worjh2_FeMahowald2006_FpCO2_Fp13CO2_A2_02180PgC_FALK`

The *forcing* includes the A2 CO_2 emissions scenario, with the annual emissions (CO_2 flux) `biogem_force_flux_atm_pCO2_sig.dat` in units of PgC yr^{-1} (== GtC yr^{-1}), hence requiring a units conversion setting in the *user-config* (`bg_par_atm_force_scale_val_3=8.3333e+013`) that is provided for you. (You can completely ignore the carbon isotope settings.)

The *forcing* also includes a prescribed dust flux to the ocean surface. This is necessary because the model configuration you are using includes a co-limitation of biological productivity by iron (Fe) in addition to phosphate (PO_4). Files are included for the time-dependent control of the supply of dust (`biogem_force_flux_sed_det_sig.dat`) as well as a prescribed spatial pattern its deposition to the ocean surface (`biogem_force_flux_sed_det_SUR.dat`). You do not need to edit these files. For the role of iron in controlling ocean productivity: possible starting points for background reading are: *Ridgwell and Kohfeld* [2007] (PDF available form my website) or *Jickells et al.* [2005] (*Science*).

The example geoengineering scenario provided to you is:

- **Enhanced weathering** (`worjh2_FeMahowald2006_FpCO2_Fp13CO2_A2_02180PgC_FALK`) (alkalinity addition)

  A constant (with time) flux of alkalinity is specified in:
  `biogem_force_flux_ocn_ALK_sig.dat`. The magnitude of the applied flux is then scaled in the *user-config* by the setting:
  `bg_par_ocn_force_scale_val_12=5.0e+13`
  Again, another example total flux. In choosing a total flux to apply, points of comparison include whatever the total weathering flux (via rivers) of alkalinity (often described in terms of the bicarbonate ion flux) to the global ocean is. Also: global cement (lime) production. (Note that in one mole of lime: CaO, you have 2 moles of alkalinity (Ca^{2+}).)

  A spatial pattern of the flux is also defined, in the file:
  `biogem_force_flux_ocn_ALK_SUR.dat`
  Again, an example pattern has been set – here, bordering the major tropical coral reefs

locations in the Western Pacific. In choosing your regions(s), you might think about mitigating specific ecosystem impacts of ocean acidification, or about the feasibility of transport and proximity to abundant limestone ($CaCO_3$ – the source of lime) and/or energy.

There is little literature on liming the ocean. It is sometimes called 'enhanced weathering' or 'artificial weathering'.

1.3 The spatial patterns of an applied flux *forcing* to the ocean can easily be modified. The pattern is specified in a simple ASCII (plain text) file, in the file in the forcing sub-directory ending '`_SUR.dat`'. The file (here for the default ALK (lime) pattern) looks like:

```
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
  0   0   0   0   0   0   0   0   0 0.0   0   0   0   0   0   0   0   0   0 0.0 0.0   0   0 0.0 0.0 0.0 0.0 0.0   0   0   0   0   0   0   0   0
  0   0   0   0   0   0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0   0   0   0   0   0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0   0   0   0   0   0   0   0
  0   0   0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0   0   0   0   0 0.0 0.0 0.0 0.0 0.0   0   0   0   0   0   0   0   0   0   0   0
  0   0   0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0   0   0   0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0   0   0   0   0   0   0   0
  0   0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0   0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0   0   0   0   0   0   0   0
  0   0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0 0.0 0.0   0   0   0   0   0   0   0   0
  0   0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0   0   0   0
  0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0   0 0.0 0.0   0   0   0   0   0   0   0
  0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0   0   0   0   0   0   0   0   0
  0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0   0   0   0 0.0 0.0   0   0   0
  0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0   0   0   0 0.0 0.0   0   0   0
  0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0   0   0   0 0.0 0.0   0 0.0 0.0
  0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0   0   0   0 0.0 0.0 0.0 0.0 0.0
  0 1.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0   0   0   0 0.0 0.0 0.0 0.0 0.0
  0 1.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0   0 0.0 0.0 0.0 0.0 0.0   0   0   0   0   0   0 0.0 0.0 0.0 0.0 0.0
  0 0.0 1.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0 0.0 0.0 0.0 0.0 0.0 0.0
  0   0 1.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0 0.0 0.0 0.0 0.0 0.0 0.0
  0   0 1.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0 0.0 0.0 0.0 0.0 0.0 0.0
0.0   0 1.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0   0 0.0 0.0 0.0 0.0 0.0   0   0   0 0.0 0.0 0.0 0.0 0.0 0.0
0.0   0 0.0 1.0 1.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0   0 0.0 0.0 0.0 0.0 0.0   0   0   0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0   0   0 1.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0   0 0.0 0.0 0.0 0.0 0.0   0   0   0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0   0   0 1.0 1.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0   0 0.0 0.0 0.0 0.0 0.0   0   0   0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0   0   0 0.0 1.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0 0.0 0.0 0.0 0.0 0.0   0   0   0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0   0   0   0 1.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0 0.0 0.0 0.0 0.0 0.0   0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0   0   0   0 1.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0   0   0   0 1.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0   0   0 1.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0   0 1.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
  0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0
  0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0
```

Here: '`0`'s represent land and cannot have a forcing associated with them. '`0.0`'s represent a zero flux, and '`1.0`'s the default forcing pattern – here, off of the coast of Australia and SE Asia. Note that a distinction is made between a '`0`' and a '`0.0`' so that you can make out where the continents are and do not necessarily have to count in the 'i' and 'j' grid directions to find a specific location. The grid is the same as you saw previously in the ocean circulation tracing Lab, and which numbered the 'i' and 'j' axes if that helps.

There is no more to changing the pattern of the flux forcing than simply marking with a '`1.0`' where you would like the forcing applied, and a '`0.0`' where it should not be. Note that there should be a single blank line at the bottom of the file. (If you have problems applying a modified spatial pattern – check that this is present.) It is best to keep a copy of the original *forcing* in case you make a mess of the spatial pattern file, but the original can also be recovered from the code server.

1.4 **Suggestions and hints on investigations assessing whether ocean carbon geoengineering is an effective means for reducing future ocean acidification and marine ecological impacts**

- Although you may want to be more creative, you do not necessarily need to run future scenarios past the end of the century.
- Impacts and ecosystems of interest could potentially be deep ocean floor, such as cold-water (deep water) corals. Don't forget that different calcifying organisms employ different mineralogies (calcite vs. aragonite), with different saturation states and hence potentially susceptibility to ocean acidification. Read some literature …
- By default, the CO_2-climate feedback is 'on':

  ```
  # set no climate feedback
  ea_36=y
  ```

  Should you want to assess the impacts of geoengineering independently of changes in climate -- the option is there. (Note that under some of the high end CO_2 emissions scenarios, there may be a degree of collapse of the AMOC that will presumably affect the patterns of ocean acidification).

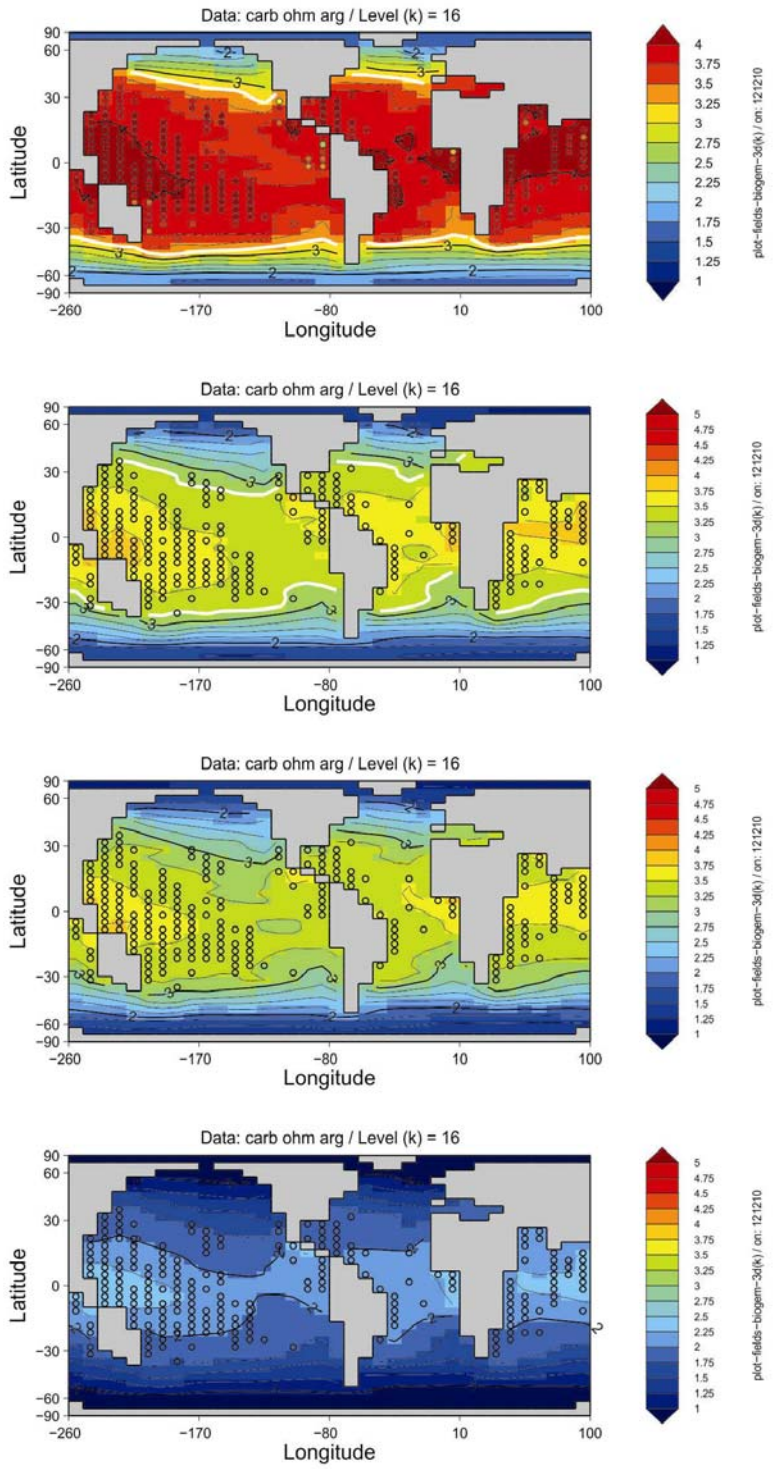
- If you are having doubts that your geoengineering experiment is actually ‘doing’ anything – remember to create anomaly maps (plots) to look for specific changes in e.g. saturation state, *p*H, or the water column inventory of anthropogenic CO_2. Even before this – plot anomalies of the flux you think you have applied, looking specifically at the region you think you have applied it to. For this, cGENIE saves the 3D distributions of dissolved ALK. See Figures below.
- Always be aware of the caveats regarding this specific model (and models in general) – how much does it different form the ‘real world’ for the modern ocean, particularly in terms of patterns of carbonate saturation? Does it even simulate anthropogenic CO_2 uptake adequately in the first place (e.g. see session **`#0100`**)?

1.5 Finally … Other manipulations of the ocean carbon cycle are possible and potentially instructive, although in the following example, rather more of relevance to past climates and carbon cycles particularly atmospheric CO_2 concentrations at the last glacial, as opposed to geoengineering …

- **CaCO3:POC rain ratio**. Kicked off by a classic 1994 Nature paper by Archer and Maier-Reimer (see: *Kohfeld and Ridgwell* [2009]), one potential means of changing atmospheric CO_2 naturally at the last glacial involves changes in the export ratio between $CaCO_3$ (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 <u>less</u> acidic glacial (compared to modern) ocean led to <u>increased</u> calcification and $CaCO_3$ export. Note that this response (higher saturation == great calcification) is encoded into your model configuration – see *Ridgwell et al.* [2007b]. In GENIE, the $CaCO_3$:POC rain ratio is controlled (technically: scaled) by the parameter: `bg_par_bio_red_POC_CaCO3=0.04`

  The pattern of $CaCO_3$: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`.

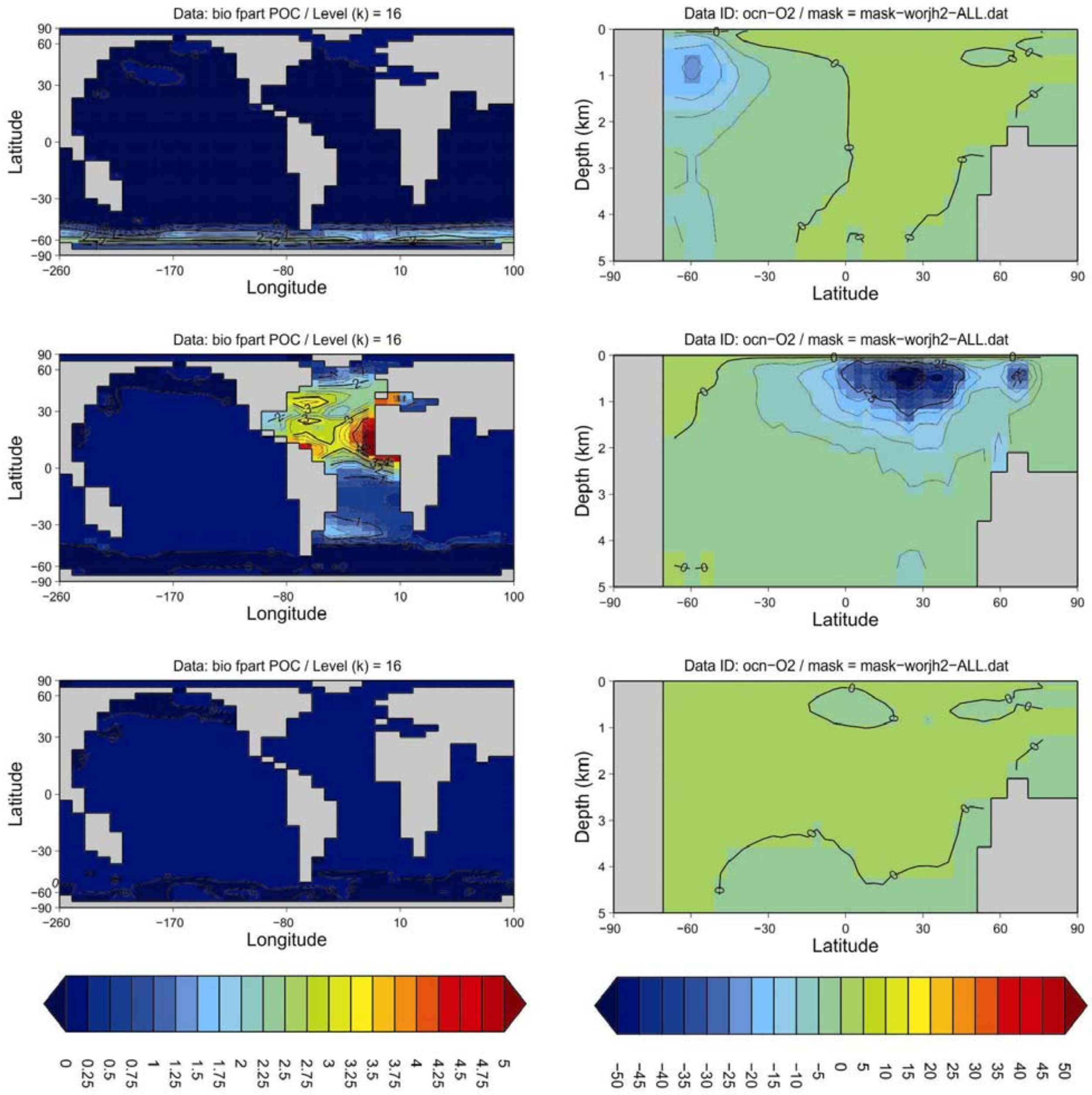
  Note that it is unlikely that there is any parallel in a geoengineering context to this process.



Mean annual ocean surface saturation (aragonite) changes.

Top: pre-industrial model ocean surface saturation (aragonite) with ReefBase tropical coral reef locations re-gridded to the GENIE grid and color-coded with modern observationally-based saturation values.
2nd and 3rd down: Year 1994 and 2010 ocean surface saturation (aragonite) with ReefBase reef locations.
Bottom: Year 2010 ocean surface saturation (aragonite) under the A2 CO_2 emissions scenario.
The thick white line delineates the 3.25 saturation contour (inferred to reflect a limitation on corals).

Examples here produced using MATLAB (plotting scripts are located in genie-matlab) but equally do-able in Panoply with the exception of achieving a data overlay. These are provided simply to illustrate some of the impacts you might consider and possible ways of visualizing them.



Ocean surface export (particulate organic carbon) and zonal $[O_2]$ anomalies.

Left: anomalies of global mean annual export production, for Fe fertilization (top), PO_4 addition (middle), and ocean liming (bottom).
Right: Zonal mean anomalies of dissolved O_2 concentrations.

Examples here produced using MATLAB (plotting scripts are located in genie-matlab) but equally do-able in Panoply with the exception of achieving a data overlay. These are provided simply to illustrate some of the impacts you might consider and possible ways of visualizing them.