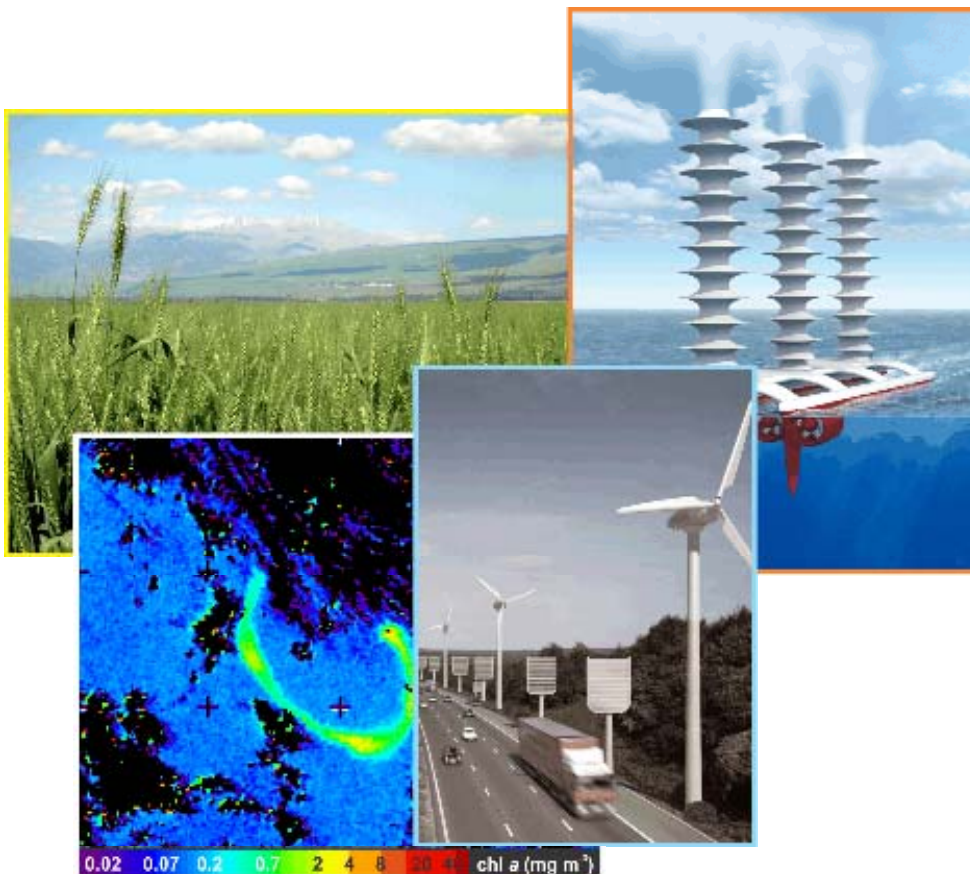# A Hitchhikers Guide to the Black Arts
(of Earth system modelling)

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/AWI.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 For the next experiment(s) you are going to explore some of the ocean biological controls on atmospheric pCO$_2$ (and surface ocean geochemistry and ocean acidification) – highly relevant to the question of why atmospheric pCO$_2$ at the time of the last glacial was ~30% lower than both prior and following interglacial times, as well as to future global environmental change and 'geoengineering'.

You will be running future CO$_2$ emissions scenarios and testing whether ocean carbon geoengineering is 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**).

1.1 A template 'A2' emissions *user-config*: `LAB.0101.GEO` is provided. This includes parameters for controlling 3 different possible ocean carbon geoengineering schemes, described below. By default, these are <u>commented out</u> (== 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 <u>control</u> (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 Each of the example geoengineering scenarios are delineated by a specific *forcing*, constituting a set of files in a uniquely named sub-directory within `genie-forcings`. They are:

- `worjh2_FeMahowald2006_FpCO2_Fp13CO2_A2_02180PgC_FFe`
- `worjh2_FeMahowald2006_FpCO2_Fp13CO2_A2_02180PgC_FPO4`
- `worjh2_FeMahowald2006_FpCO2_Fp13CO2_A2_02180PgC_FALK`

Each *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.)

Each *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 details of the 3 different example geoengineering scenarios provided to you are:

- **Iron fertilization** (`worjh2_FeMahowald2006_FpCO2_Fp13CO2_A2_02180PgC_FFe`)

  A constant (with time) flux of dissolved Fe (in addition to whatever Fe dissolves into the surface ocean from the dust flux) is specified in: `biogem_force_flux_ocn_Fe_sig.dat`. The magnitude of the applied flux is then scaled in the *user-config* file by the setting: `bg_par_ocn_force_scale_val_9=1.0e+09`
  Note that this is simply an <u>example</u> total global flux. You may consider higher or lower fluxes, as well as potentially how 'practical' the annual production and supply of such quantities might be. Contrasting in your paper whatever flux you decide on, with natural Fe

fluxes, either globally or regionally, would provide a useful point of comparison for the reader.

A spatial pattern of the flux is also defined, in the file:
`biogem_force_flux_ocn_Fe_SUR.dat`

An <u>example</u> pattern is set (see Section 1.3 for details on editing this pattern) – here a row of grid cells at the same latitude in the Southern Ocean. You do not need to retain this pattern. In choosing an alternative: think (and do some background reading) on whether in the modern ocean biological productivity is thought to be at least partly limited by the availability of dissolved Fe. Remember that the model may or may not correspond with reality, i.e. it may or may not predict Fe limitation in the correct regions, which may affect your choice of location for iron fertilization as well as informing your discussion.

There is abundant literature: on the natural Fe cycle in the ocean and Fe limitation of productivity, on experiments carried out to fertilize ocean biota, on model studies of natural Fe cycling and also some model studies on deliberate Fe fertilization (plus papers on feasibility and ethical considerations).

- **Phosphate fertilization** (`worjh2_FeMahowald2006_FpCO2_Fp13CO2_A2_02180PgC_FPO4`) ('macro-nutrient' addition)

  A constant (with time) flux of dissolved PO_4 is specified in:
  `biogem_force_flux_ocn_PO4_sig.dat`. The magnitude of the applied flux is then scaled in the *user-config* by the setting:
  `bg_par_ocn_force_scale_val_8=2.0e+12`
  Again, you should consider this as an <u>example</u> total flux (i.e. it is not a 'correct' answer!). In choosing a total flux to apply, points of comparison include whatever the total weathering flux (via rivers) of P to the global ocean is. Also: global phosphate (fertilizer) production, which produces an interesting potential conflict between geoengineering and food production, although there are proposals for using fertilized ocean regions for enhanced fish production.

  A spatial pattern of the flux is also defined, in the file:
  `biogem_force_flux_ocn_PO4_SUR.dat`
  Again, an <u>example</u> pattern has been set – here, the Equatorial Atlantic. In choosing your regions(s), think about where in the ocean (again – there may be differences between real ocean and model) productivity is currently limited by PO_4. Also be aware of possible on-set of Fe limitation if you relieve the PO_4 limitation (i.e., you could potentially lose effectiveness if you supply too much PO_4 and instead productivity and CO_2 drawdown is capped by a second factor). You could potentially consider PO_4 and Fe addition at the same time … ?

  There is some literature on macro-nutrient addition to the ocean. This often focuses on nitrate (NO_3) rather than PO_4, but you can treat them as effectively interchangeable, i.e. we could have set the model up with NO_3 instead of PO_4 as the sole potentially limiting macro-nutrient in the ocean and your results and conclusions would effectively be the same.

- **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 <u>example</u> 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 <u>example</u> 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 Fe 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 0.0   0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
  0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0 0.0 0.0 0.0 0.0 0.0 0.0   0   0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
  0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0 0.0 0.0 0.0 0.0 0.0   0   0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0   0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0 0.0 0.0 0.0 0.0 0.0   0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0   0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0 0.0 0.0 0.0 0.0   0   0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0 0.0 0.0 0.0   0   0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0 0.0 0.0 0.0   0   0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0 0.0 0.0 0.0   0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0   0 0.0 0.0 0.0   0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0   0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0   0   0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 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 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 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 0.0 0.0 0.0 0.0 0.0   0
  0   0   0   0   0   0   0   0   0   0   0   0   0   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 Southern Ocean forcing pattern. 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 are free to be more creative, it is practical only to run the future scenarios just to the end of the century and not to worry about emissions past year 2100 or the total fossil fuel CO_2 'burn' we might eventually manage.
- 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.
- Some of the arguments against some forms of ocean carbon geoengineering concern the potential for adverse impacts on marine organisms (and positive climate feedbacks) induced by decreases in the degree of oxygenation in the ocean, such as expanding and/or intensifying oxygen minimum zones. (*c*GENIE saves 3D fields of O_2 concentrations.)

- If you want to combine *forcings*, you need to firstly update the file: `configure_forcings_ocn.dat` – this specified which ocean flux forcing will be used – simply copy the relevant line from the equivalent file of the *forcing* to be added. You will also need to copy in the relevant '`_sig.dat`' and '`_SUR.dat`' files. Remember that in the *user-config* file, you will need to set the relevant flux scaling parameter for each different flux in the *forcing*.
- By default, the CO_2-climate feedback is 'on':
  ```
  # set no climate feedback
  ea_36=y
  ```
  It is unlikely that you will want it 'off', but the option is there is you need it. (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 Fe, PO_4, and ALK (alkalinity). 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 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.
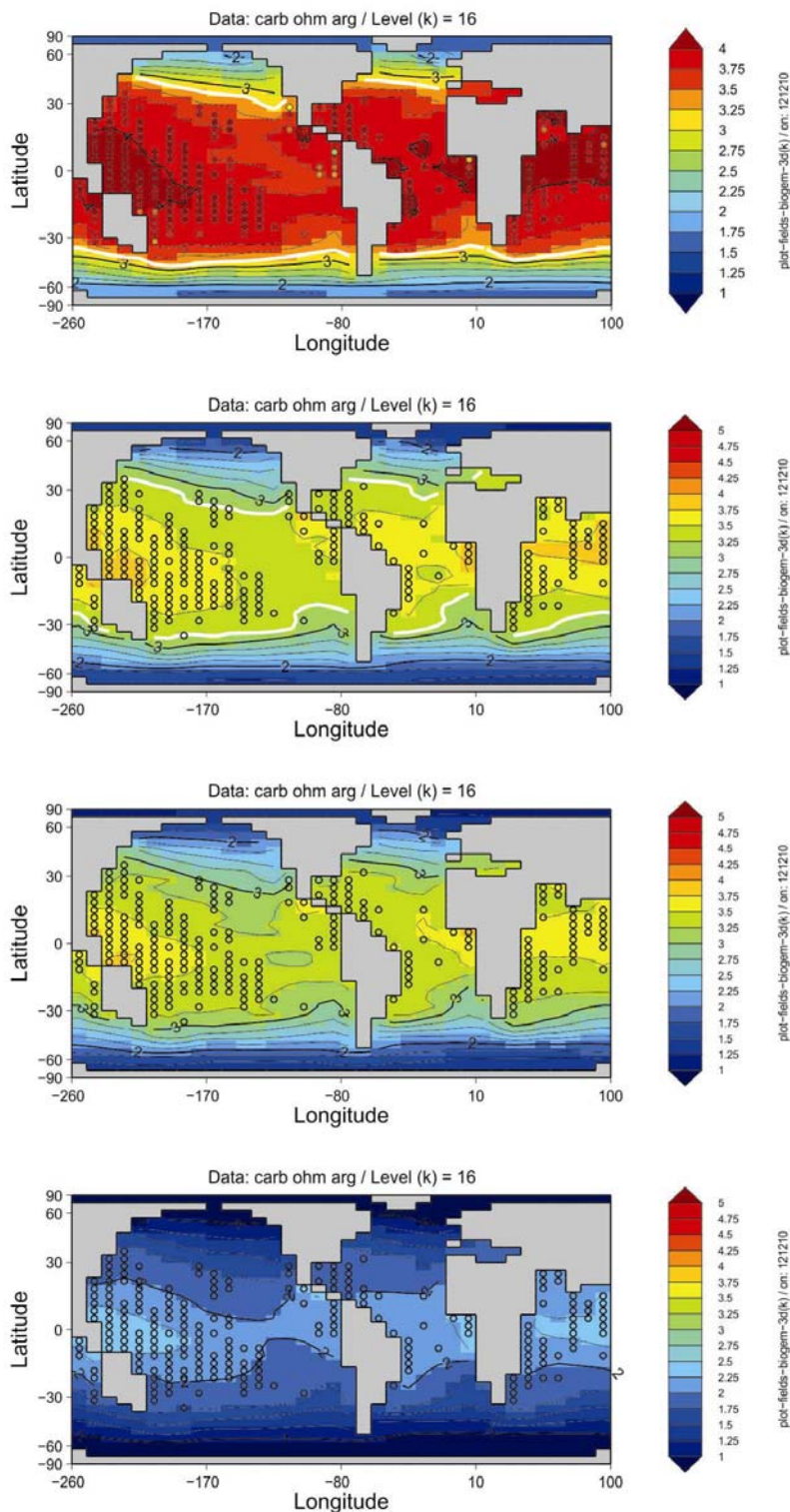
**Mean annual ocean surface saturation (aragonite) changes.**

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 down: Year 1994 ocean surface saturation (aragonite) with ReefBase reef locations.

3rd down: Year 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).
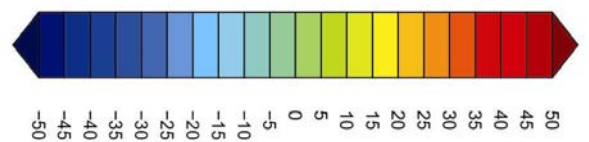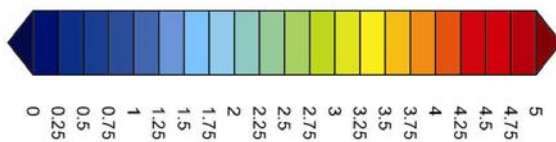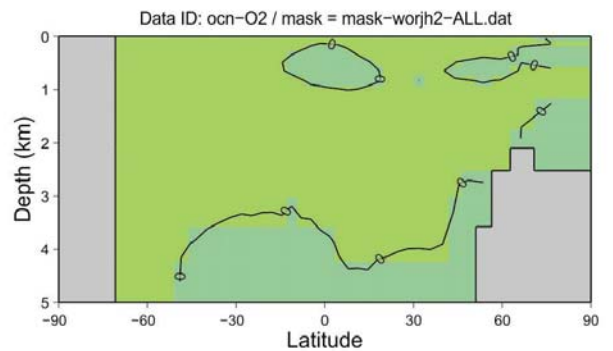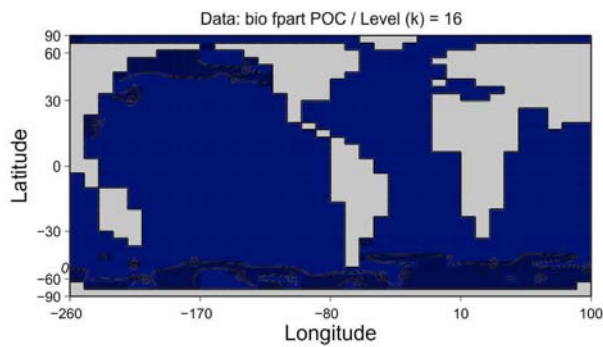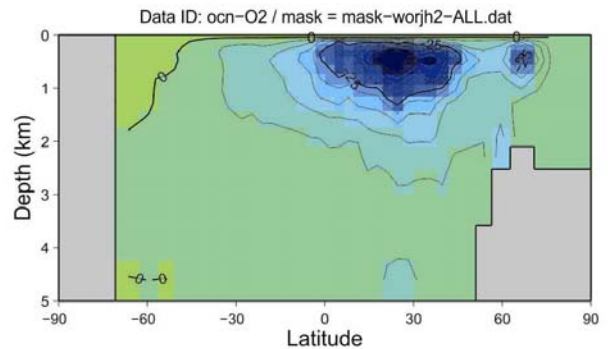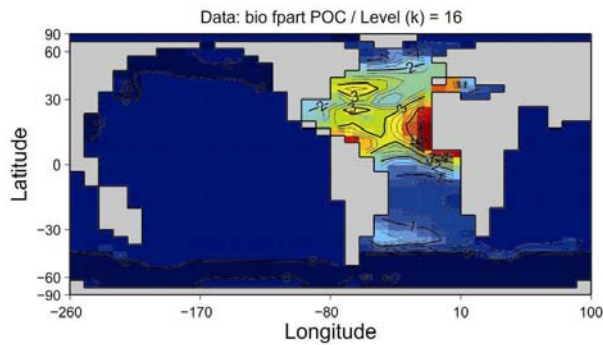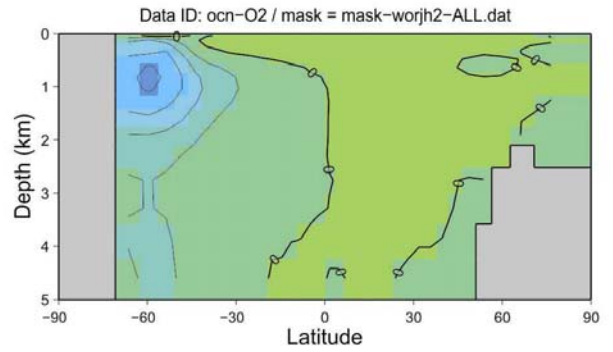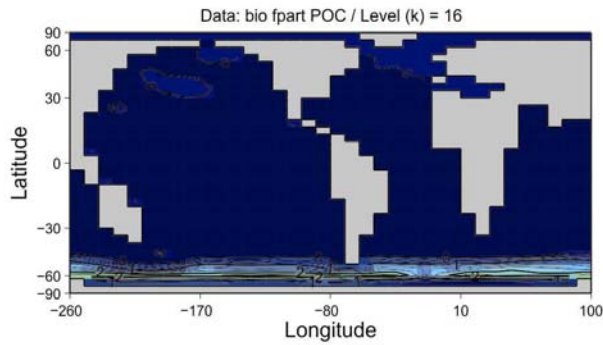
Ocean surface export (particulate organic carbon) and zonal [O₂] anomolies.

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.