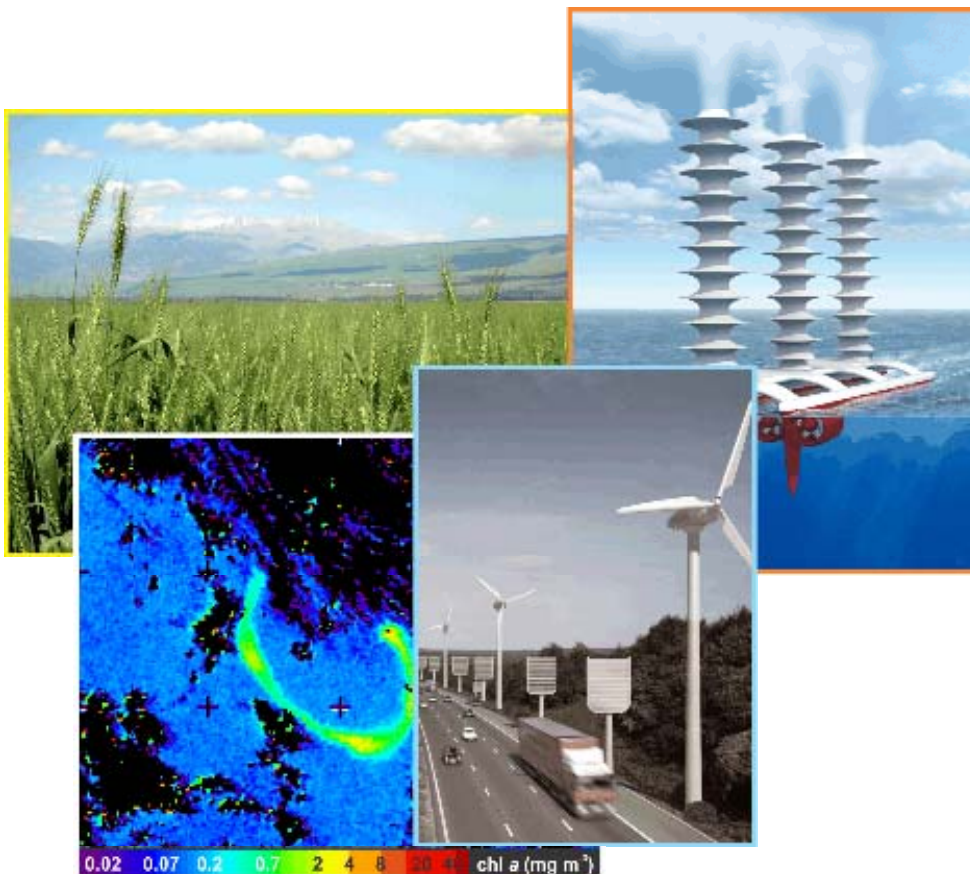


A Hitchhikers Guide to the Black Arts (of Earth system modelling)

PART #0101: Engineering the carbon cycle



0. Readme

0.0 If you have not been through (and completed!) Session #0100 ('Fossil fuel CO₂ 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/LATP.2013/EXAMPLE.worjh2.PO4Fe.HISTORICAL.tar.gz
```

Extract the contents of this archive by typing:

```
$ tar xfv 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 explore some of the ocean biological controls on atmospheric $p\text{CO}_2$ (and surface ocean geochemistry and ocean acidification) – highly relevant to the question of why atmospheric $p\text{CO}_2$ 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 $p\text{CO}_2$ 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 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 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 from 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 example 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 example 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 example 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 example 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 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

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 CO₂-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 if you need it. (Note that under some of the high end CO₂ 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, pH, or the water column inventory of anthropogenic CO₂. 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, PO₄, and ALK (alkalinity). See Figures below.
 - Always be aware of the caveats regarding this specific model (and models in general) – how much does it differ from the 'real world' for the modern ocean, particularly in terms of patterns of carbonate saturation? Does it even simulate anthropogenic CO₂ 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.
- 1.6 Finally ... Other manipulations of the biological pump and ocean carbon cycle (more of relevance to past climates and carbon cycles as opposed to geoengineering) are possible and potentially instructive:

- **Remineralization depth.** The degradation of particulate organic matter in the water column proceeds according to a fixed profile of flux with depth (there is no e.g. temperature control on the rate of bacterial degradation of sinking organic matter in this particular configuration) with CO₂ and PO₄ released back to the seawater as the particulate flux decreases. The parameter that controls the (e-folding) depth scale of particulate organic matter is:

```
bg_par_bio_remin_POC_eL1=589.9451
```

Either edit this value (under heading: # --- REMINERALIZATION ---) or add a new line at the end of the *user config* file specifying the value you want. Units are m.

Read *Ridgwell et al.* [2007] for additional discussion of this parameter. See Figure 2-4 in *Ridgwell* [2001] (http://www.seao2.org/pubs/ridgwell_thesis.pdf) for an illustration of how the flux of particulate organic matter decreases with depth in the ocean, plus references therein.

There is also an associated parameter: *bg_par_bio_remin_POC_frac2*, which sets a fraction of organic matter that is assumed to settling through the water column completely un-altered (currently assigned a value of 0.045 == 4.5%), but this is arguably less appropriate to change than the remineralization length-scale of the more labile fraction (97.5% of exported particulate organic carbon).

Note that there may well be no simple parallel in a geoengineering context to this process, although industrially, coagulating and methods for accelerating the setting of often organic particles from solution are common. However, there are hypotheses that during the last glacial and as a result of colder ocean temperatures, the depth scale was longer.

Conversely, there are ideas about that the warmer temperatures of the e.g. Eocene ocean and hence faster rates of bacterial metabolism led to a much shallower remineralization depth scale.

- **Macro nutrient inventory and uptake.** Suggestions have been made that nutrients were used more efficiently during the LGM, meaning that for the same nutrient uptake at the surface more carbon was exported to depth in the ocean. See: *Omta et al.* [2006]. There

are also a bunch of (relatively old) hypotheses concerning differences between glacial and modern ocean in how much nitrate (NO_3^-) there was. There is no NO_3^- in this version of GENIE (just PO_4^{3-} and Fe), but an analogous change can be made to the phosphorous cycle.

For the nutrient-to-carbon ratio in organic matter, the relevant parameter is:

```
bg_par_bio_red_POP_POC=106.0
```

To change the default value (106.0), add a new line at the end of the *user-config* file specifying the value you want. A larger number means that PO_4 is being utilized more efficiently and more organic matter is being produced for the same nutrient consumption. To test the effect of there being more PO_4 in the ocean, in addition to using the (surface) flux forcing as described earlier, it is also possible to simply increase the inventory of the ocean as a whole in one go:

```
bg_ocn_dinit_8=1.0E-6
```

which will add $1 \mu\text{mol kg}^{-1}$ of PO_4 uniformly to the ocean. (A larger/smaller number will obviously increase the glacial nutrient inventory by more/less.)

In terms of geoengineering, changing the 'Redfield' ocean plankton might be difficult ... but not impossible, although we are presumably talking releases of genetically modified organisms to the entire ocean and hence there are obviously some severe ethical concerns. However, adding macro nutrients such as PO_4 (more often, NO_3 is talked about) may be more feasible. There are obvious examples of paleo relevance, e.g. associated with Ocean Anoxic Events.

- **CaCO₃:POC rain ratio.** Kicked off by a classic 1994 Nature paper by Archer and Maier-Reimer (see: *Kohfeld and Ridgwell* [2009]), one means of changing atmospheric CO_2 that has been proposed 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 less acidic glacial (compared to modern) ocean led to increased calcification and CaCO_3 export. Note that this response (higher saturation == great calcification) is encoded into your model configuration – see *Ridgwell et al.* [2007b].

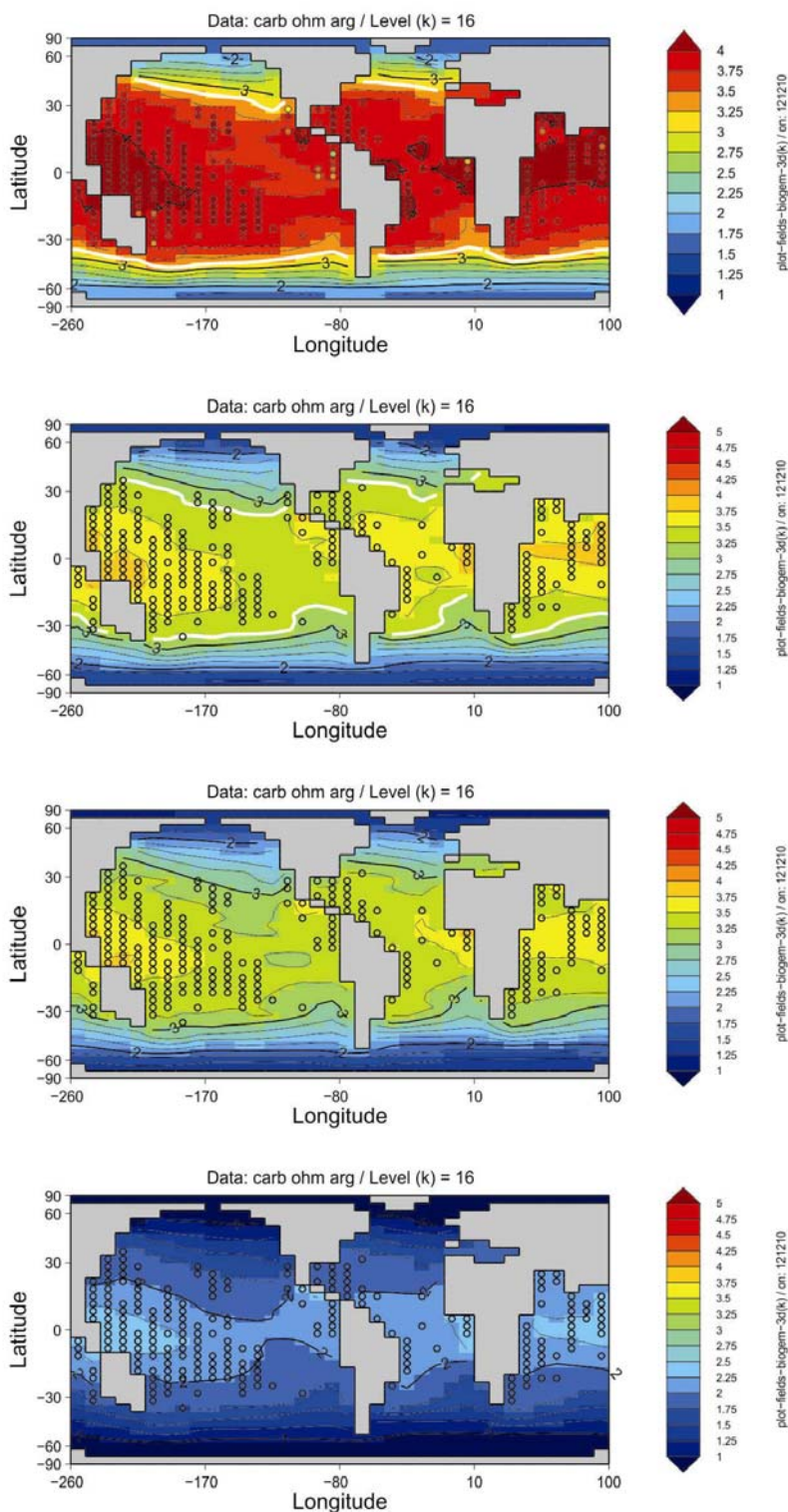
In GENIE, the CaCO_3 :POC rain ratio is controlled (technically: scaled) by the parameter:

```
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.

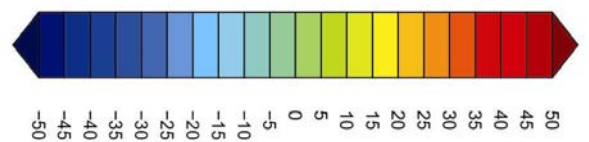
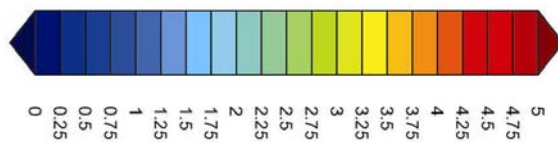
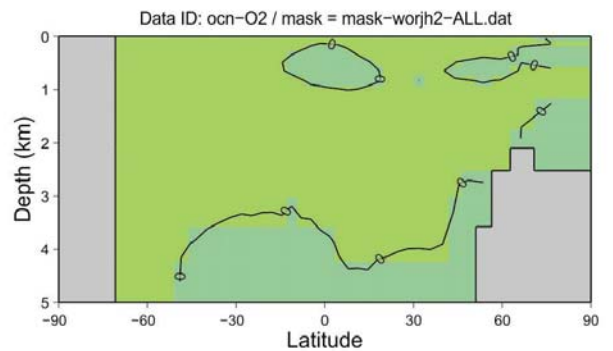
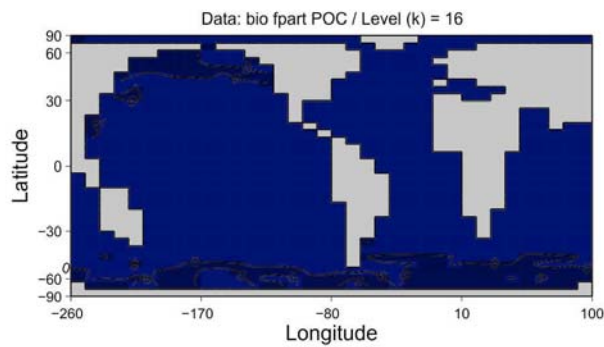
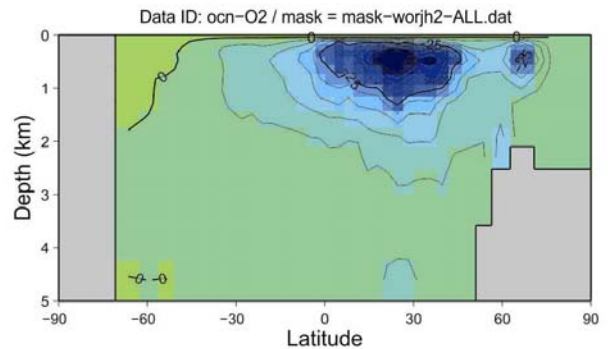
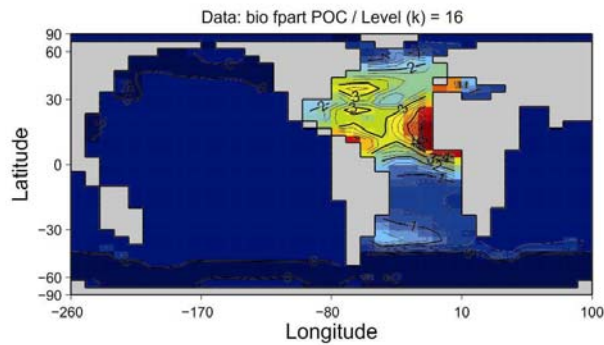
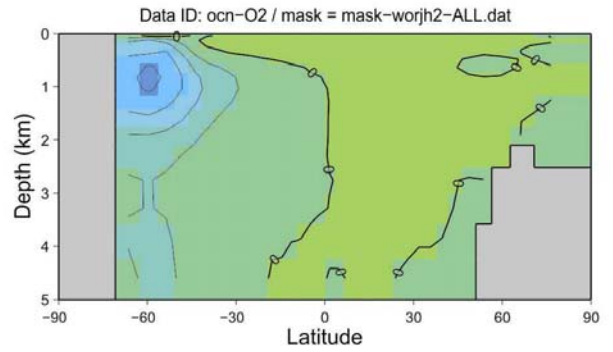
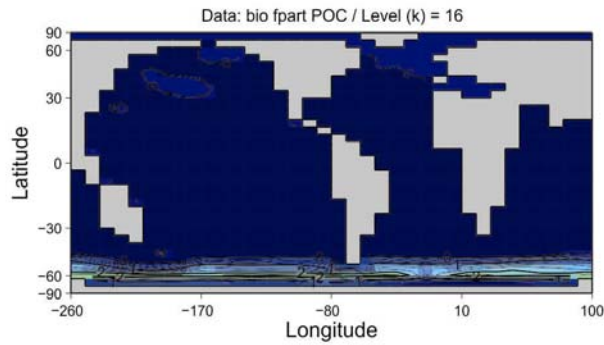
Top: pre-industrial model ocean surface saturation (aragonite) with ReefBase tropical coral reef locations re-gridded to the GENIE grid and color-coded with modern observationally-based saturation values.

2nd 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 CO₂ 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] anomalies.

Left: anomalies of global mean annual export production, for Fe fertilization (top), PO₄ addition (middle), and ocean liming (bottom).

Right: Zonal mean anomalies of dissolved O₂ concentrations.