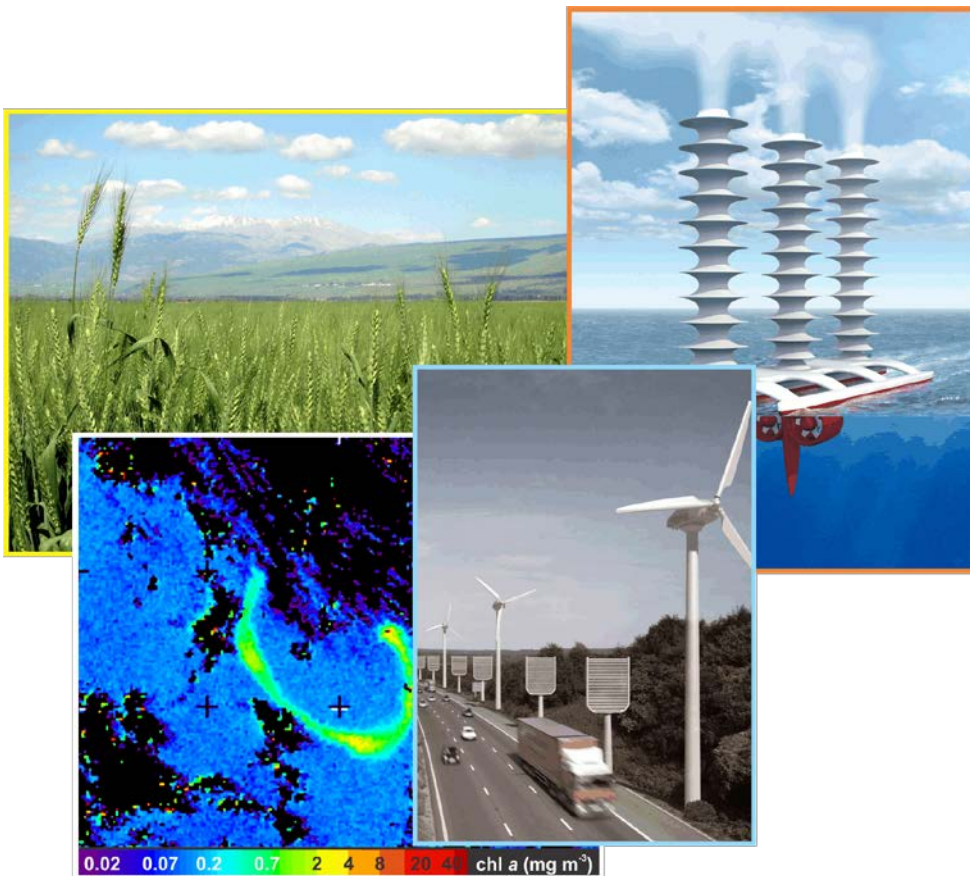# A Hitchhikers Guide to the Black Arts
(of Earth system modelling)

`Lesson #4:` Engineering the carbon cycle and the 'biological pump'

0.   Readme

0.0   You will need to download a new *restart* file prior to embarking on the experiments. This differs from previous provided *restarts* in that it now includes an iron cycle in the ocean and hence co-limitation of biological productivity by Fe.

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

`$ wget http://www.seao2.info/cgenie/labs/AWI.2017/LAB_4.SPIN.tar.gz`

Extract the contents of this archive by typing:

`$ tar xfzv LAB_4.SPIN.tar.gz`

(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 pCO$_2$ (plus ocean acidification, and the distributions and intensities of oxygen minimum zones). Really, the 'geoengineering' focus is just an excuse to be looking at how the biological pump in the ocean works, how it regulates atmospheric pCO$_2$, how sensitive it is to perturbation and what the consequences are of any changes in it. So if you are uncomfortable with ideas of large scale manipulating the Earth system, think about the relevance of the experiments to e.g. understanding why atmospheric pCO$_2$ was low at the time of the last glacial.

The overall idea of this lab is to run future CO$_2$ emissions scenarios and test whether ocean carbon geoengineering is an effective means for reducing future ocean acidification and marine ecological impacts (but keep in mind you are also exploring the basic natural operation of the system in doing so). You will require a pre-industrial spin-up and will need to create a new historical pCO$_2$ transient experiment because compared to the previous lab, you are now using a different *base-config* (cgenie.eb_go_gs_ac_bg.worjh2.BASEFe) that includes additional tracers for the marine iron cycle, i.e. you cannot simply use any of the experiments from previous labs as a *restart*.

1.1   So to start with, go ahead and run a new historical transient experiment. A *user-config* is provided for your convenience (LAB_4.historical) … but maybe check the settings for e.g. start year, as well as note that there are a number of new parameters to control the iron cycle (amongst other differences) as compared to before:

```
$ ./runmuffin.sh cgenie.eb_go_gs_ac_bg.worjh2.BASEFe LABS
 LAB_4.historical 245 LAB_4.SPIN
```

(ignore the 'WARNING's at the start)

1.2   An example *user-config* is provided: LAB_4.EXAMPLE. This includes parameter settings for controlling any one of 3 different possible ocean carbon geoengineering schemes, described below (Section 1.3). 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 by default. You might regard this as a <u>control</u> (reference) experiment for all the with-geoengineering experiments you might run, i.e. the impacts of CO$_2$ emissions in the absence of any mitigation by geoenginerring. To activate any particular geoengineering *forcing*: simply un-comment (delete the #) 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). If you have multiple (un-commented) settings of a parameter (e.g. bg_par_forcing_name) the value specified in the last occurrence is the one that is applied. This can get confusing, so if you un-comment out one set of parameter options, comment out (add a #) the ones you are not using.

The geoengineering (and control) experiments need to be run starting from the end of your historical transient experiment:

```
$ ./runmuffin.sh cgenie.eb_go_gs_ac_bg.worjh2.BASEFe LABS
 LAB_4.EXAMPLE 90 LAB_4.historical
```

Because with a modern configuration and additional tracers in the ocean, the model is running rather slower than in some earlier exercises, you may not want to run beyond the end of the century (hence the 90 year experiment duration, starting from year 2010, as suggested above).

1.3   Each of the example geoengineering scenarios are delineated by its own specific *forcing* – a set of files that live in a uniquely named sub-directory within genie-forcings. The three *forcings* 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 under the heading `# CO2 emissions scaling`. (You can completely ignore the carbon isotope settings.)

Each *forcing* also includes a prescribed dust flux to the ocean surface (the `FeMahowald2006` part of the directory name string). 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). (The files associated with the dust forcing are: `biogem_force_flux_sed_det_sig.dat` and `biogem_force_flux_sed_det_SUR.dat` but 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 specific details of the 3 different example geoengineering scenarios 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 might consider higher or lower fluxes, as well as potentially how 'practical' the annual production and supply of such quantities might be.

  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 1.4 for details on editing this pattern) – here a row of grid cells are marked at the same latitude in the Southern Ocean. You do not need to retain this pattern. In choosing an alternative: think about where 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.

- **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. 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 … ?

- **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.

1.4 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 (in this example the default Fe pattern) looks like:

```
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```

Here: '`0`'s represent land and cannot have a forcing associated with them. '`0.0`'s represent a zero flux to the ocean, 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. For the ALK *forcing*, '`1.0`'s are set off of the coast of Australia and SE Asia and in the PO$_4$ *forcing*, in the Atlantic.

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. <u>Note that there should be a single blank line at the bottom of the file</u>. (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.

2. Further ideas

2.0 **Impacts to look out for**

- Impacts and ecosystems of interest could potentially be ones residing on the ocean floor, such as cold-water (deep water) corals, and are not necessarily planktic (/surface) only.

- Don't forget that different calcifying organisms employ different mineralogies (calcite vs. aragonite), with different saturation states and hence potentially susceptibility to ocean acidification. Hence thresholds of both aragonite and calcite saturation will be relevant, depending on the organism. Depending on the organism, saturation changes occurring in specific regions may much more relevant than a global mean change. Also, it might be the seasonal minimum value reached, rather than annual averaged minimum, that is critical.

- 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 that can be plotted in slices through the ocean of various orientations.

2.1 **Further modifications of the biological pump in the ocean**

Other manipulations of the biological pump and ocean carbon cycle are possible and potentially instructive and in the following examples may be of rather more relevance to past climates and carbon cycles and e.g. possible reasons for the low atmospheric CO_2 concentrations at the last glacial, as opposed to relevant to geoengineering (a good thing!). The first two of these may have profound effects not only atmospheric pCO_2 but also on dissolved oxygen concentrations in the ocean (and hence implications for the suitability of animal habitat such as for fish) and this is something that you will want to look at as part of your overall assessment of impacts.

- **Remineralization depth**. In the model configuration that you have been using, the degradation of particulate organic matter sinking 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) with CO_2 and PO_4 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 (found under the 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 settle through the water column completely un-altered (currently assigned a value of `0.045` == 4.5%), but this is arguably less useful to change than the remineralization length-scale of the more labile fraction (the other 95.5% of particulate organic carbon exported from the ocean surface).

  Note that there may well be no simple parallel that can be found in geoengineering to this process. 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. So a remineralization depth scale that is responsive to temperature may have importance in understanding ocean biogeochemical cycles during both past warm and cold climates as well as obviously, future global change. While you are not implementing a temperature-dependent parameterization explicitly, you can at least test for whether changes in temperature might have important impacts by simply changing the remineralization depth to be shallower (smaller depth-scale under a warming climate) or deeper (greater depth-scale in a colder ocean).

- **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 μmol 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 about releases of genetically modified organisms to the entire ocean to achieve this meaning 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.

- **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.)

2.2 Other thoughts and suggestions

- If you want to combine *forcings*, you need to first update the file:
  `configure_forcings_ocn.dat` – this specifies 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 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 and oxygenation etc.)

- If you are having doubts that your experiment is actually 'doing' anything (different from the control) – 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 and PO_4. 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 **#2**)?
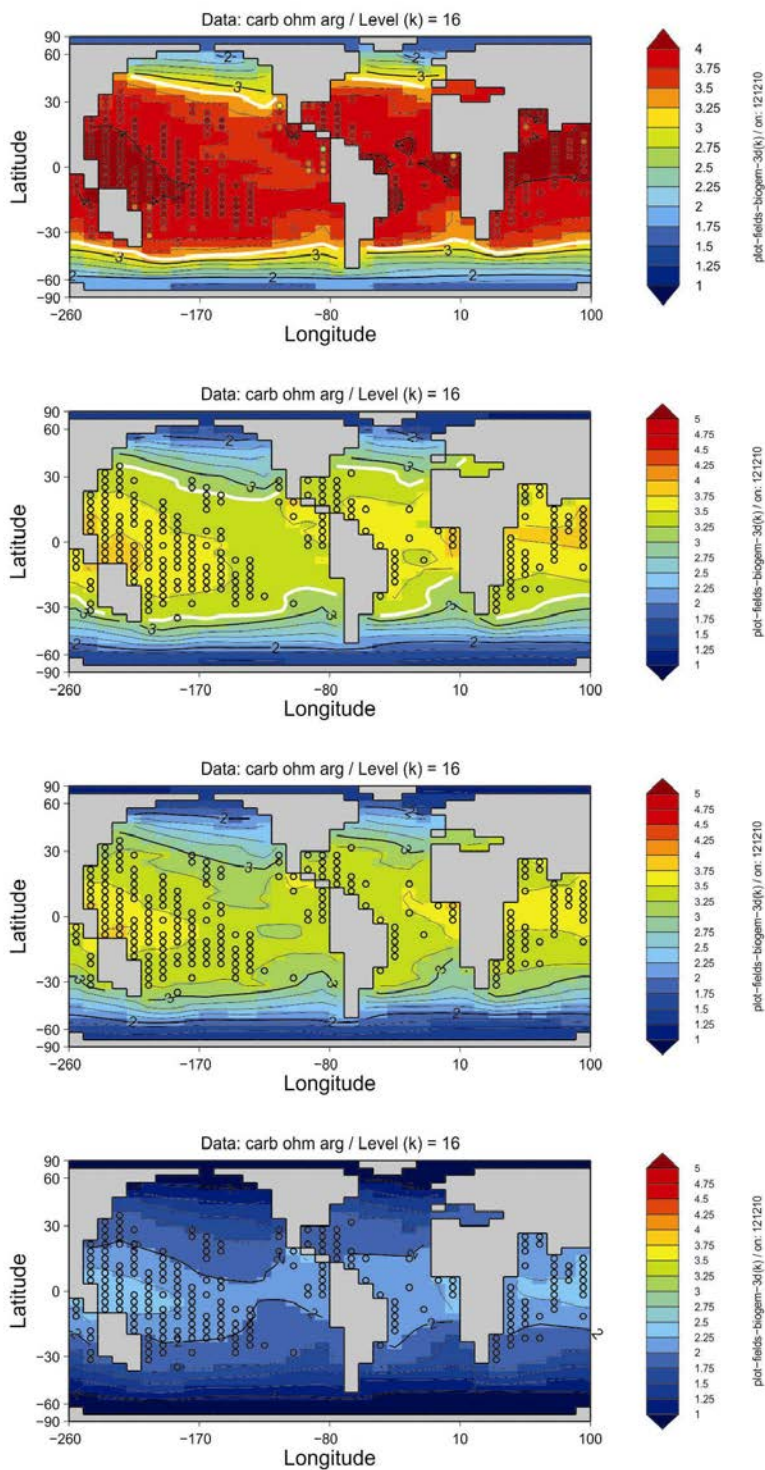
Mean annual ocean surface saturation (aragonite) changes.

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.

9
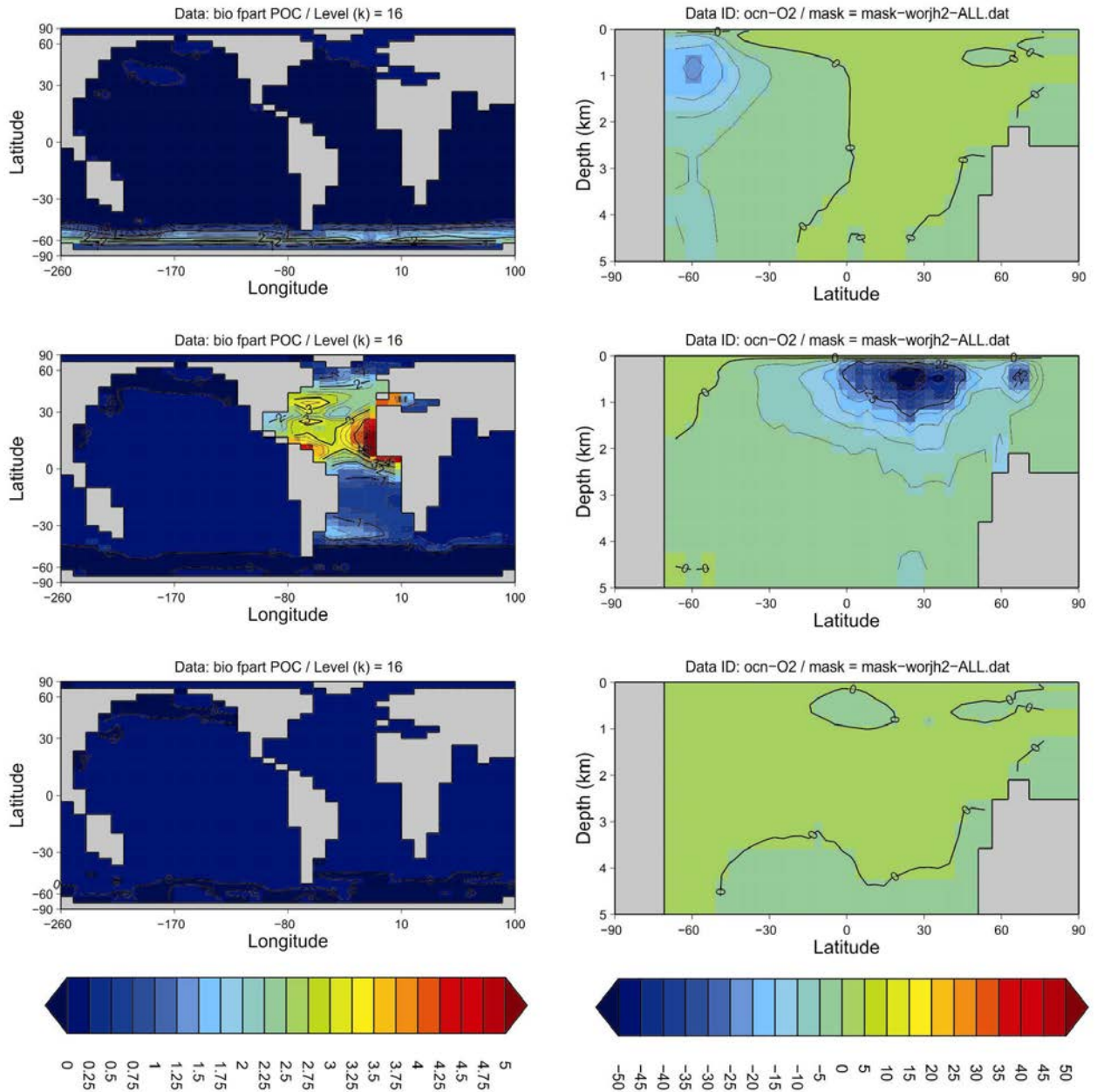
Ocean surface export (particulate organic carbon) and zonal [O₂] anomalies.

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.

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.