

A globe of Earth is shown from a perspective that includes North and South America. The globe is semi-transparent, revealing a background of binary code (0s and 1s) in a light green color. The text is overlaid on the globe.

Introduction to Earth system modelling

Andy Ridgwell

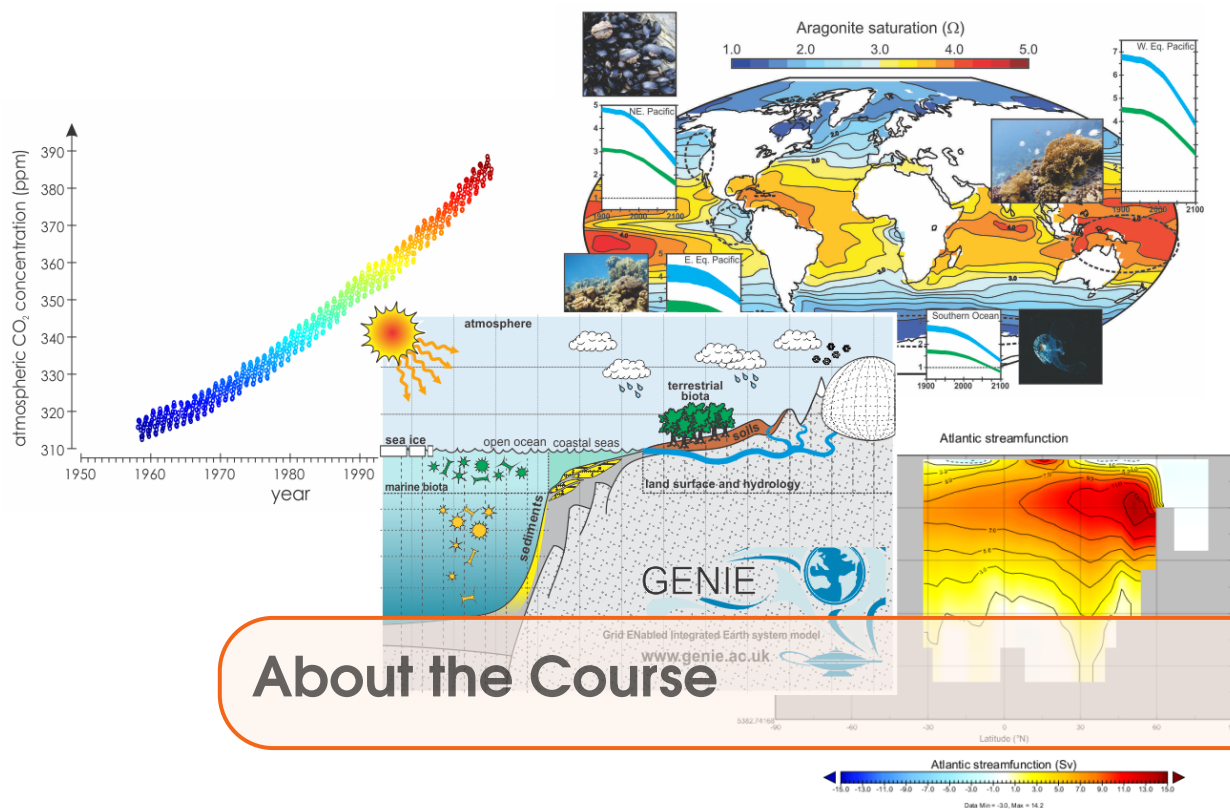
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First printing, October 2017



About the Course

This course will provide an introduction to, and practical hands-on learning in, Earth system modelling and dynamics. It will provide a chance to explore the dynamics of the Earth's climate system as well as of global carbon cycling (and other biogeochemical cycles) and include topical issues of past (geological) global change as well as a wide range of potential future global environmental impacts of fossil fuel CO₂ emissions and concepts in mitigation and geoengineering. But equally, the course will exemplify how numerical models can be utilized to address scientific questions, test hypotheses, and quantify the past and future relationship between global carbon cycling and climate and associated feedbacks. The course will facilitate the development of a variety of new computer skills and experience with data analysis and visualization techniques. The cumulating objectives of the course are to develop a deeper understanding of the role and nature of feedbacks in the Earth system and provide context to the impacts of current human activities and also and importantly, foster a critical appreciation of the nature and limitations of climate and Earth system modelling in understanding and predicting global change.

Upon completion of the course, you will be expected to have gained through hands-on practical exploration, factual knowledge and a mechanistic understanding of:

- The role and nature of feedbacks in the climate system and how climate is 'regulated', including the relationship and associated feedbacks between climate and global carbon cycling.
- The primary controls on global ocean circulation patterns and stability.
- The primary global climatic, biogeochemical, and ecological consequences of continuing fossil fuel CO₂ emissions, plus the practicality and effectiveness of geoengineering.
- The primary controls on biological productivity and carbon storage, in the ocean and on land.
- The long-term (geological) regulation of global climate and atmospheric CO₂.
- The use of numerical models in addressing scientific questions and testing hypotheses, as well as the limitations of numerical model representations of climate dynamics and global carbon cycling.

The course will provide transferable skills in:

- Written communication and presentation.
- Problem solving and quantitative analysis.
- Working in a unix-based computer environment, basic data analysis and computer programming in MATLAB plus techniques of data visualization, including both time-series and netCDF format spatial data.

Course details

Format

The weekly format of the Class is: 1 × 3-hour computer practical session, plus 1 × 3-hour interactive lecture/discussion session of worked problems and examples. The computer practical class is the central element, and will consist of structured exercises leading step-by-step through configuring, running, and analysing the **cGENIE.muffin** (hereafter: 'muffin') Earth system model and using this to explore a series of basic assessments as well as topical issues in global carbon cycle and climate dynamics. The purpose of the 3-hour lecture/discussion session ending the week is to critically assess a published model and/or model-based scientific finding, using the **muffin** model as a tool to help further explore the assumptions made.

Each week, the Lab will take place on Wednesdays from 2:00 pm to 4:50 pm in Watkins 2111, and the Lecture/Discussion on Fridays, 9:00 am to 11:50 am (also in Watkins 2111). The first class of the course will be on Wednesday 2nd October at 2:00 pm in Watkins 2111.

Timetable

The timetabling and overall course structure of GEO290 are given in Table 1.

Table 1: Schedule of GEO290

Week #	Wednesday LAB	Friday Discussion/LAB
01 (09/30)	GENIE modelling basics.	snowball Earth!
02 (10/07)	Exploring the nature and dynamics of ocean circulation.	The climatology of past worlds.
03 (10/14)	MATLAB and model data visualization & analysis.	The climatology of past worlds. (CONTINUED)
04 (10/21)	CO ₂ emissions, ocean acidification, and climate change.	The ocean's biological pump, and iron and phosphate cycling.
05 (10/28)	Marine ecology.	Marine ecology and the biological carbon.
06 (11/04)	<i>Group project work</i>	<i>Group project work</i>
07 (11/11)	Group Presentations	Marine ecology and biogeochemical cycles in past worlds.
08 (11/18)	Atmospheric dynamics and coupled (GCM) climate modelling.	GCMs (CONTINUED)
09 (11/25)	Paleoclimate. proxies, and model-data comparison.	UCR HOLIDAY
10 (12/02)	<i>Individual project work.</i>	<i>Individual project work. (CONTINUED)</i>

Assessment

The course will be assessed as follows:

- Midterm / group presentations – 40%
- Finals / individual paper – 60%

The Mid-term assessment will be in the form of a group presentation, presenting the results of a short model-based investigation carried out in the week (or weeks) beforehand. The topic can be based on anything in the course up to that date. The presentation is expected to be 20-30 minutes long (ca. 10 minutes per person) and all group members must participate. There will be questions, both from the instructor and audience (remainder of the class) following. Perhaps your thesis advisor will be there ;)

The Finals assessment will be based upon an Earth system model based research investigation – guidance will be provided as to potentially suitable topics along with detailed background and suggestions for investigative directions and experiment design. The assessment will be in the form of a written report in a Nature Article format. Marking and feedback will be based on the quality of article, appropriateness of the modelling methodology and its description, depth and innovation of the model (and model-data) analysis, adequate appreciation of the literature, a demonstrated awareness of model limitations plus critical assessment of the caveats to the approach and results, and ability to convey information and concepts to a relatively general audience.

Office Hours

There are no specific Office Hours, but rather an open invitation to drop by¹ (excluding Thursdays) and/or email² questions. Tuesdays (almost any time) would be your best chance of finding me (and not busy).

Course text

The course is based on a text containing a series of tutorials surrounding different elements of, and topics, in Earth system dynamics and global biogeochemical cycles, that can be found [here](#). (Additional sets of topical and focussed readings can be found therein.) A guide to using this text, specific weekly topics and activities, and assessments, will be provided on the first day of class.

Course technical details

Logistics

The labs are based around using and analysing the ‘**muffin**’ Earth system model³. You will be working in small groups (e.g. 2) and will be remote accessing a computing cluster (where the model will actually run)). You will hence need some means of accessing the remote computer. Unless you are some sort of wizard, I suggest a lab desktop, or your own laptop, connected to the internet.

In terms of group working dynamics – if everyone each brings a laptop, then in a group of 2 it becomes easier to be e.g. managing configuring and running the model on one laptop, and analysing results or displaying instructions/documentation on another other.

Required software

If you chose to use a lab desktop, which will be a Windoz 10 based machine, all the software you need will be pre-installed.

¹My office is in the Geology building, room 464 (basement floor).

²andy@seao2.org

³<http://www.seao2.info/mycgenie.html>

If you plan on using your own laptop to remote access the model and visualize results, you will need some specific software. The exact software will depend on your operating system, but everyone will need:

1. A terminal ('shell') window. This is no problem for linux and Mac users (you already have one built in). For Windows, either download a simple (and old) SSH client (ssh-client) from my website⁴ or you can get hold of e.g. PuTTY (<http://www.putty.org/>).
2. A sftp (secure file transfer) client for convenience (i.e. dragging and dropping files between local and remote computers, and opening files directly on the remote computer cluster). If you have installed ssh-client (Windows, above) then a sftp client is already included as part of this software. If using PuTTY (Windows) you might try downloading WinSCP (<http://winscp.net/eng/index.php>). For the Mac – I am told that Cyberduck is OK (there are bound to be many other alternatives). For linux, maybe FileZilla.
3. A viewer for netCDF format spatial data. A Java viewer called Panoply is provided by NCAR for all platforms – <http://www.giss.nasa.gov/tools/panoply/> (Note that you will need Java installed!)
4. A simple text editor, except not the rubbish default Windows one – you need one that can display unix ASCII text without screwing it up. Options for Windows users are: notepad++ (<https://notepad-plus-plus.org/>) SciTE (<https://sourceforge.net/projects/scintilla/>) (linux and Mac users need no special/different editor compared with your standard editor – everything will display just fine).

Further details are provided in the [muffin manual](#).

Running cGENIE.muffin on a laptop

It is also possible to install and run the **muffin** on a linux box (e.g. Ubuntu) or a Mac. Instructions are provided in the [muffin manual](#).

Note that it is not possible at this time to run the 'muffin' version of **cGENIE** under Windows (at least, not without near infinite pain). A version that will compile under Windows is under development as [Project cupcake](#).

Also note that if you have trouble installing and running **muffin** on your own linux box or Mac, there may not be time to sort out the problem. If so, you'll have to access and run the model remotely. (There are also advantages to running on the remote cluster as you will see in due course.)

⁴<http://www.seao2.info/cgenie/software/ssh-client.exe>

Assignment – Mid-term presentation

Instructions

In groups: carry out an investigation using the **muffin** model on any scientific question related to the material covered in the class to date. The investigation should not simply be a repeat of course material and you need to go 'beyond' the material provided in some way.

You should aim to formulate a hypothesis, or series of hypotheses, that you test using the model. Ideally, the questions addressed will have an interesting purpose and point, relevant to e.g. to past or future climate change or some fundamental process in the modern ocean.

Format

The presentation will be to the entire class and be given by the group, with each group member participating. The suggest duration of the presentation is ca. 5-10 minutes per person (with a suggested minimum total presentation length of 10-15 minutes). The form of the presentation should be in the style of a slightly extended conference presentation.

Other

The presentation constitutes 40% of the course marks.

Assignment – Finals project

Instructions

Carry out an investigation using the **muffin** model ... and write it up! Thats it!

(OK, some more info.)

The investigation can be based on facets of the Earth system (as represented in **muffin**) that have been covered in the course, or it could go beyond that. The investigation could also build on specific experiments and investigations from the course, or be a completely new and different research topic.

However, the investigation should not simply be a repeat of course material. You should also avoid doing something that is only incrementally different from a course experiment/investigation.

You should aim to formulate a hypothesis, or series of hypotheses, that you test using the model. Ideally, the questions addressed will have an interesting purpose and point, relevant to e.g. to past or future climate change or some fundamental process in the modern ocean. Indeed, in the introduction and background of the paper, you will be needing to set the scene and describe the relationship of your study to the relevant literature.⁵

Format

For the format – follow the '[manuscript formatting guide](#)' guide for Nature. Use the instructions for writing a Nature 'Article', e.g.:

- <3000 words for the main text
- no more than 5-6 Figures (and Tables)
- a brief model and methodology description should be included in a 'Methods' section (see Nature guidelines)

If you would like to show additional model plots and/or description that is not central to the conclusions of your paper – you can include a separate section of '[Supplementary Information](#)'.

You do not have to number the references: writing them out as e.g. '*Watson et al.* [2000]' rather than reference '(3)' or '3' in the main text is fine. Nor are you expected to produce a layout that looks like a published paper (although that is fine if you would like to).

Hand-in date is: 5:00 pm on Friday 13th December 2019. Hand-in is electronically by email – ideally in PDF format, but Word format files are acceptable. Ideally this should be as a single file, but it is OK to split into a maximum of 3 files: main text, figures, and Supplementary Information / Extended Methods. Please, do not send all the figures as individual files ...

Remember: Running the model experiments and the write-up must be done individually.

Other

This paper constitutes 60% of the course marks.

⁵A hypothesis and associated study based on the question: 'Does the ocean cool down if the Sun is switched off?' ... is just not going to nail it.

Specific readings

Work plan

i (Wednesday)

ii (Friday)

Cluster account configuration

1. Modelling basics &... snowball Earth!

Remember that the various course PDFs on the web <http://www.seao2.info/mymuffin.html> ... the course guide as well as the **muffin** manual ... may be updated from class-to-class, and you'll need to be always working from the current version. To do this and to force a re-load of the webpage cache in your browser:

- Windows – press the Ctrl-F5 key combination.
- Mac – according to Google (and I am unable to test this) ...
"In Camino and Firefox, press Shift-Command-R (or hold Shift and click the Reload button).
In Safari, hold the Option key and press the Reload button in the toolbar."

1.1 Specific readings

- Snowball Earth review:
Hoffman and Schrag [2002] (Terra Nova 14, 129-155)
- Model analysis of the inception of a snowball Earth and ice-albedo thresholds:
Hyde et al. [2000] (Nature 405, 425-429)

1.2 Work plan

The work plan for week #1, is to:

1.2.1 i (Wednesday)

Work through Chapter #1, and specifically:

- Section 1.1 – Basic notes on working methodology and software required.
For users of WinSCP, there is a convenient way to configure this to enable you to edit files on the remote server directly. By default, if you double-click on a file in the remote server window (the left hand window), then the file is opened. However, by default, a text file

might be opened by Notepad (bad). So in the **WinSCP** Options menu, and the item Preferences, which opens a settings window:

Under Editors – you can add e.g. Notepad++ and associated this with text files. You could also add Panoply and associated with .nc (netCDF) files. Tick the 'Force text transfer ...' check box.

It remains that the easiest way to copy files is to drag them locally, rename them (maybe then edit and save them), and drag them back.

If you set this up correctly, then you can double-click a remote file, edit it, and save it, and the updated file contents will be written back to the remote computer.

- Section 1.2 – Logging in and accessing, configuring, and testing the code.

In 1.2.2 – Use `git clone` to get the code.

Refer to the end of this chapter for notes on configuring the cluster account.

In 1.2.3 – Your cluster is 'domino' (when it comes to which file is to be edited). Note the footnote explanation on what 'commenting' and 'un-commenting' lines of code involves.

You can ignore 1.2.5.

- Figure 1.1 – Explore, using a file transfer client (such as **WinSCP**), the model directory structure with the figure as a guide, to help familiarize yourself with where everything is.

- Section 1.3 – Running the model.

(Also note Figure 1.2.)

- Section 1.4 – Make sure that you are familiar with where the output is, and what the different forms of output are.

Note that when you run an experiment with a different *base-config*, the model is automatically re-compiled. This is important in the context of submitting jobs to the cluster – see below.

- Section 1.5 – Make sure that you are familiar with how to view all the different sorts of model output.

- Section 1.6 – Submitting jobs to the cluster.

IMPORTANT: The first time that you want to run an experiment with a NEW *bas-config*, you need to ensure the model re-compiles. Do this by running a brief interactive experiment at the command line. Only then, is it 'safe' to submit to the cluster.

Note that if you have multiple experiments to submit to the cluster, all using the same *base-config*, you only need to ensure the recompile for the first experiment (and then only if the *base-config* is different from the the last experiment you ran).

- Section 1.7 – *Re-starts*. Be sure to be clear in your mind, that a *re-start* is just a 'normal' experiment that has been previously run. Any new experiment can start from the end of that previously-run experiment.

1.2.2 ii (Friday)

Work through Chapter 2, and specifically:

- Section 2.1. There are 2 sperate exercises to be done here:
 - (1) Running multiple model experiments to determine the approximate radiative forcing CO_2 threshold that would induce a snowball climate state.
 - (2) Using an experiment in which a snowball state occurs as a *re-start*, determine the radiative forcing threshold required to exit that state.
- Additional/optional – Explore the use and effect of different continental configurations – Section 2.2.2 and/or Section 2.2.3.

- Completely optional – Section 2.2.4 and 2.2.5 (and 2.2.1).

1.3 Cluster account configuration

In order to fully configure your cluster account and enable the **muffin** model to work, you need to edit a special file that is read-in when you log in, and directs **muffin** to some software libraries that it needs.

The file lives in your home directory (the directory you log into), and is called:

```
.bash_profile
```

Now unfortunately ... this file is a 'hidden' file ... to see it at the command line you cannot just type `ls` to display the directory listing, but rather, you need:

```
$ ls -la
```

In your file transfer client, you need to find somewhere in the settings where it will show 'hidden' files in order to be able to see it.

You will need to open, edit, and save this file, which can be done:

1. Directly in a command-line editor such as Vi.
2. Indirectly, by dragging the file locally, editing, saving, and dragging back (but remember that your file transfer client needs to be able to 'see' the hidden file in the first place).
3. By – if you have set up your file transfer client in this way – double-clicking the file, editing and saving. (But you still need to be able to 'see' it!)

At the end of `.bash_profile`, add the following lines:

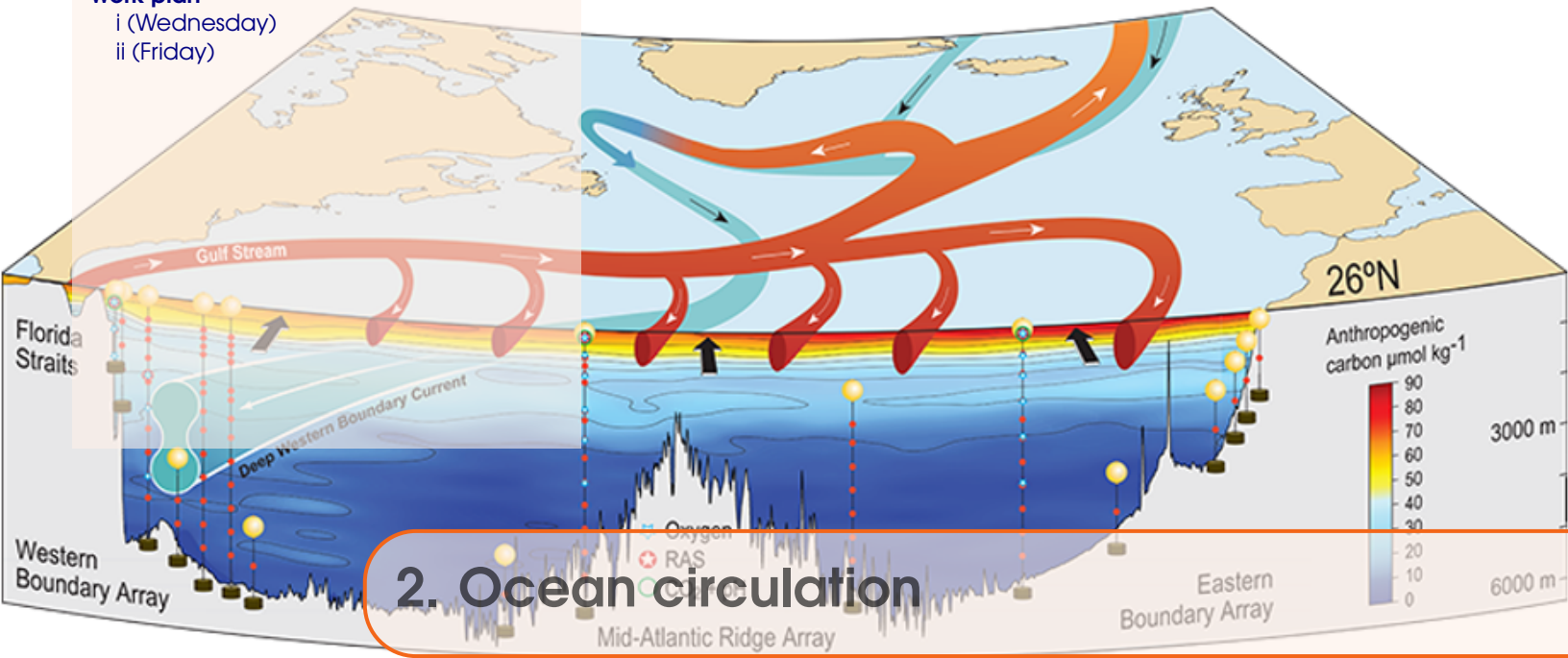
```
# User specific environment and startup programs
PATH=$PATH:$HOME/bin
export PATH
PATH=$PATH:/state/partition1/apps/netcdf-c-4.4.1.1-fortran-4.4.4/lib
export PATH
PATH=$PATH:/state/partition1/apps/netcdf-c-4.4.1.1-fortran-4.4.4/include
export PATH
LD_LIBRARY_PATH=$LD_LIBRARY_PATH:/state/partition1/apps/netcdf-c-4.4.1.1-fortran-4.4.4/lib
export LD_LIBRARY_PATH
export CGENIE_PYTHON=/state/partition1/apps/Python-2.7.13/bin/python2.7
```

You can copy-paste from this document ... with care. Or find the information from the following [link](#).

Specific readings

Work plan

- i (Wednesday)
- ii (Friday)



From last week – updates and points to note, are:

1. When ... and only when changing a *base-config* for your next experiment, will you need to re-compile the model before submitting a job to the cluster.
e.g. if you had just been running experiments with a *base-config* file *base1*, and then you want to change continental configuration defined by *base-config* file *base2*, you cannot directly go and submit a job to the cluster queue using *base2*. Instead, you need to start running the new experiment interactively (at the command line). `runmuffin` will recognise that a different *base-config* file is being used, and automatically make `cleanall` and then re-compiled the model. You can either run the experiment for just one year, or kill (CTRL-C) the experiment once it has started running (after completing compiling). Then, you can submit the experiment as a job to the cluster queue.
You do not need to re-compile **muffin** again until you want to switch to yet another new (or the previous) *base-config*. i.e. it is not necessary to re-compile before each and every experiment, only if the *base-config* has changed.
2. For Section 2.2.3, the key *user-config* file was not provided for you at the time ... The instructions have now been updated and the necessary file has now been added to the **muffin** code base.

To update your **muffin** code-base – from the directory `cgenie.muffin`, type:

```
$ git pull
```

Do this if you wish to re-visit and complete Section 2.2.3.

NOTE that you may be required, from time-to-time during the course, to update your installed **muffin** code base in exactly this way. (You will be notified each time when this is necessary.)

2.1 Specific readings

1. Atlantic circulation and stability in GENIE

- Simple assessment of the likelihood of AMOC collapse:
Hargreaves et al. [2004] (Climate Dynamics, Volume 23, Issue 7 - 8, Dec 2004, Pages 745 – 760)
- Characterization of thresholds of AMOC collapse.:
Marsh et al. [2004] (Climate Dynamics, Volume 23, Issue 7 - 8, Dec 2004, Pages 761 – 777)
- Role of changing ocean circulation in atmospheric radiocarbon variability during the Younger Dryas.
Singaraye et al. [2008] (GRL 35, doi:10.1029/2008GL034074)
- Deep-sea CaCO₃ sediment and atmospheric CO₂ response to AMOC shutdown:
Chikamoto et al. [2008] (JGR 113, doi:10.1029/2007JG000666)

2. Miscellaneous (model) Atlantic circulation and stability

- Background to the Atlantic Meridional Overturning Circulation and hypothesized hysteresis:
Rahmstorf et al. [2006] (In: Encyclopedia of Quaternary Sciences, Edited by S. A. Elias. Elsevier, Amsterdam)
- Future predictions of AMOC strength:
IPCC [2007] (e.g., Section 10.3.4)
- Impacts on marine ecosystems and carbon cycling:
Schmittner [2005] (Nature 434, 628– 633)
- Climate-carbon cycle model response to freshwater discharge:
Obata [2007] (J. Clim. 20, 5962–5976)

2.2 Work plan

2.2.1 i (Wednesday)

Work through Chapter #3, and specifically:

- Section 3.1 – Introducing forcings of the model and developing ways of visualizing and tracing ocean circulation in the model.
- Section 3.2 – How to force/induce changes in ocean circulation in the model. Further visualization of ocean circulation.
- (optional) – Section 3.3.1 – Exploring the sensitivity of ocean circulation to the spatial pattern/location of the (freshwater) perturbation.
- (optional) – Section 3.3.4 – Diagnosing the 'age' of a water mass.

2.2.2 ii (Friday)

1. First, read through the rather incomplete Chapter 5, which should at the very least, give you some ideas and further information on understanding/diagnosing ocean circulation in the model.
2. Next ... transfer to the cluster by wget, the following *re-start* experiment archives:

- muffin.CB.eg_ww_lo.BASES.SPIN.tar.gz
- muffin.CB.eg_rw_lo.BASES.SPIN.tar.gz
- muffin.CB.eg_ep_lo.BASES.SPIN.tar.gz
- muffin.CB.eg_ee_lo.BASES.SPIN.tar.gz

and then unpack (to *genie_output*).

Create a series of 4 new *user-config* files, each with the following contents:

```
#
# --- CLIMATE -----
#
# scaling for atmospheric CO2 radiative forcing, relative to 278 ppm
ea_radfor_scl_co2=1.0
#
# --- BIOLOGICAL NEW PRODUCTION -----
#
# Set no biological production
bg_par_bio_prodopt='NONE'
#
# --- DATA SAVING -----
#
# Set BASIC + full physics save level (9)
# (assume default time-series and time-slice save intervals)
bg_par_data_save_level=9
bg_ctrl_debug_lv10=.true.
ma_debug_loop=1
#
# --- END -----
#
```

Then you are going to need some *base-config* files. You should copy and rename the following files in *genie.muffin/genie-main/configs*:

- muffin.CB.eg_ww_lo.BASES.config
- muffin.CB.eg_rw_lo.BASES.config
- muffin.CB.eg_ep_lo.BASES.config
- muffin.CB.eg_ee_lo.BASES.config

and edit them (delete lines) such that the 'TRACER CONFIGURATION' section ends up looking like:

```
# *****
# TRACER CONFIGURATION
# *****
# the total number of tracers includes T and S
# T and S do not need to be explicited selected and initialzied
# *****
# Set number of tracers
GOLDSTEINNTRACSOPTS='$(DEFINE)GOLDSTEINNTRACS=2'
# *****
```

Basically, you are just removing all the carbon/biogeochemical cycle tracers (and leaving just temperature and salinity).

Finally, run the 4 experiments using the *re-starts* you downloaded, the new *user-config* files

you created, and the copy/edited *base-configs*. Running for e.g. 10 years is sufficient. Assess the nature of ocean circulation in the 4 different abstract continental configurations and try and deduce *why* the circulation patterns are what they are. Refer to the references given in Chapter 5.

3. The last thing to do ... is to make some 'worlds' and then run them(!) (and deduce how the ocean circulates). See Chapter 16.

Prior to the end of the class, submit your various worlds as jobs to the cluster, running for 5,000 or 10,000 years to steady state (hopefully!).



Work plan
i (Wednesday)
ii (Friday)

3. Alternative Worlds and data visualization

3.1 Work plan

3.1.1 i (Wednesday)

Fake (alternative) Worlds are a useful tool for developing a general understanding of how climate (and ocean circulation) and global biogeochemical cycles operate. Different model resolutions and continental configurations can be generated and run to test specific hypotheses about the role and sensitivity of different elements in Earth system to emergent patterns of climate (and biogeochemical cycling). Ensembles of differing Worlds can also be utilized to generalize understanding as well as in a fishing expedition of new or unexpected phenomena and system behaviours.

Generate and explore (analyse) some fake (alternative) Worlds, using the tools of diagnosis and understand ocean circulation and climate that you have already learnt.

3.1.2 ii (Friday)

First, read/work through Chapter 13 in the muffin manual.

You may need to refresh or learn a few basic MATLAB skills such as plotting of simple text (ASCII) files (but read through Chapter 13 first to see what is needed). For instance from the 'matlabanas' text book, you might familiarize yourself with Sections:

- Section 1.6 – *Loading and saving data*, and specifically, sub-sections: 1.6.1 – Where am I? and 1.6.2 – Loading and importing data.
- Section 1.4 – *Basic graphing (aka. 'data visualization')*, and specifically, sub-sections: 1.4.1 – Plotting, 1.4.2 – Graph labelling, 1.4.4 – Saving graphics and figures.

and if you need more info on concepts such as *variables* and *arrays* in **MATLAB**, first:

- Section 1.2 – *Basic concepts*, and specifically, sub-sections: 1.2.1 – Variables.

- Section 1.3 – *Vectors and arrays #1*, and specifically, sub-sections: 1.3.2 – Basic vector manipulation, 1.3.4 – Addressing elements in vectors.

Armed with this knowledge, try plotting some time-series data from your model experiments.

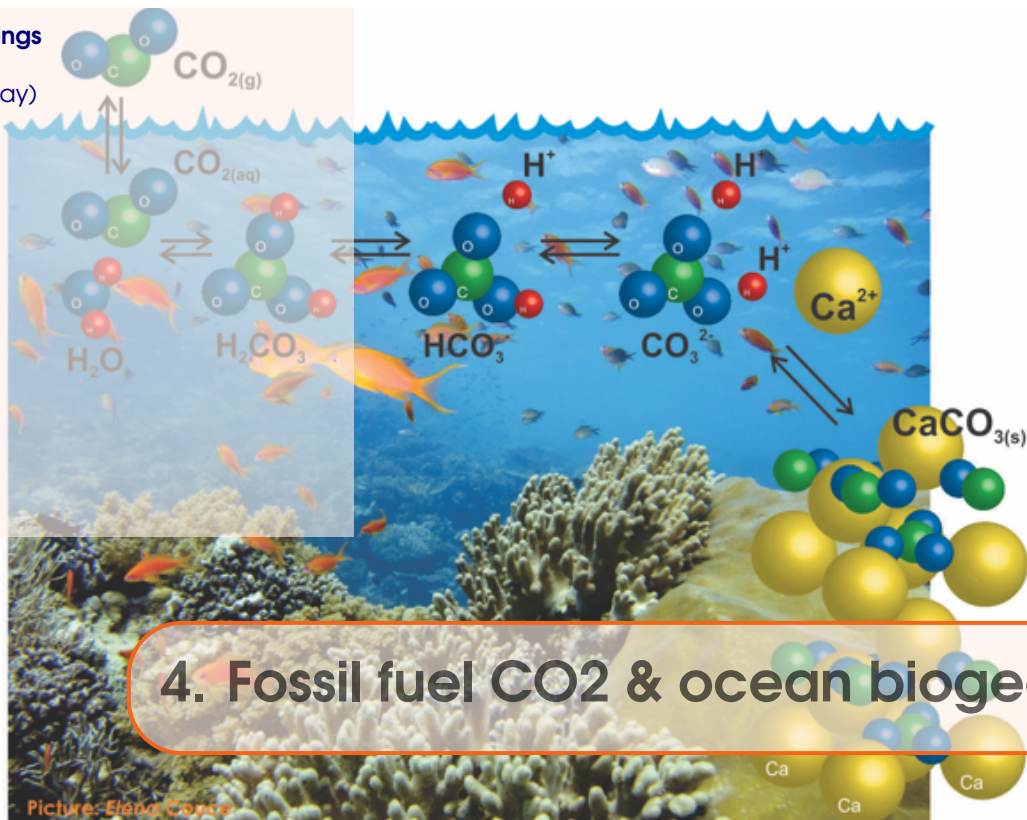
Secondly, read/work through Chapter 13 in the muffin manual.

Specific readings

Work plan

i (Wednesday)

ii (Friday)



4. Fossil fuel CO_2 & ocean biogeochemistry

Picture: Elong Corals

4.1 Specific readings

- 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. Lehoudey, 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- CO_2 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., CO_2 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/>

4.2 Work plan

4.2.1 i (Wednesday)

Chapter 6, and in particular Section 6.1 (all of), plus Section 6.2.1.

4.2.2 ii (Friday)

Using the 'excuse' of geoengineering ... perturb and elucidate the response of the global carbon cycle and climate system (and thereby hence learn something new/different about Earth system dynamics compared to e.g. its response only under standard future carbon emissions scenarios).

Sections 8.1 (al of), plus note contents of Section 8.2.1.

Specific readings

Work plan

- i (Wednesday)
- ii (Friday)

5. Marine ecosystems and dynamics

You will be working with highly idealised marine ecosystems representations ... The aim is to explore why the model behaves as it does. The assumption is that this will give us some insight into why the real world behaves as it does. Perhaps. (It is up to you to question the validity of this assumption.)

5.1 Specific readings

First read:

- Ward et al. [2017] – Ward, B. A., Wilson, J. D., Death, R. M., Monteiro, F. M., Yool, A., and Ridgwell, A.: EcoGENIE 1.0: plankton ecology in the cGENIE Earth system model, Geosci. Model Dev. DOI: 10.5194/gmd-11-4241-2018 (2018).
<https://www.geosci-model-dev.net/11/4241/2018/gmd-11-4241-2018.pdf>

5.2 Work plan

5.2.1 i (Wednesday)

Work through:

- 10.1 – *Getting going with ECOGEM*
- 10.2 – *Ecosystem configuration*
- 10.3 – *Increasing ecological complexity*

5.2.2 ii (Friday)

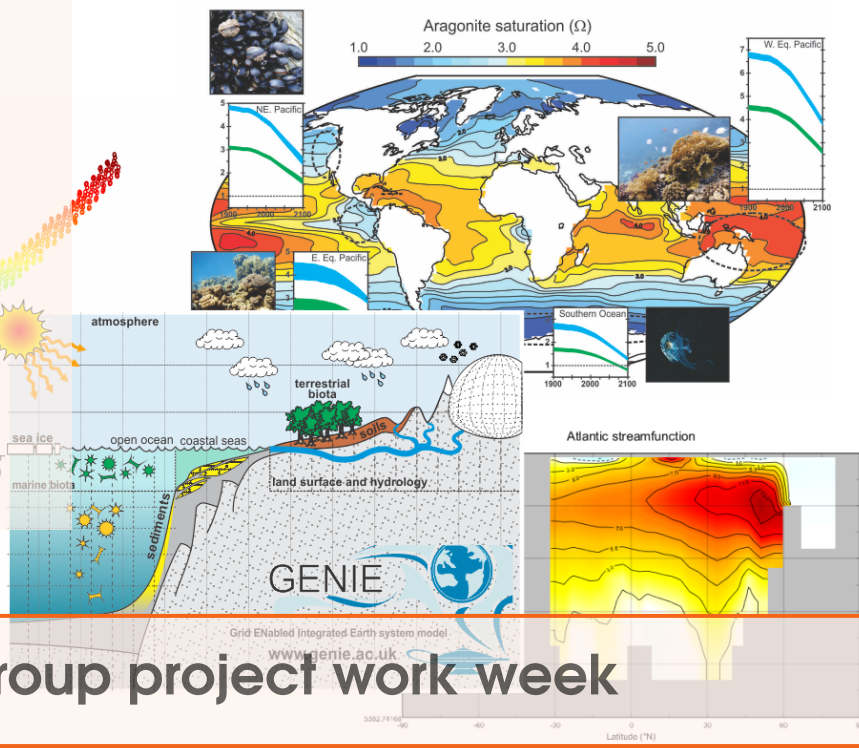
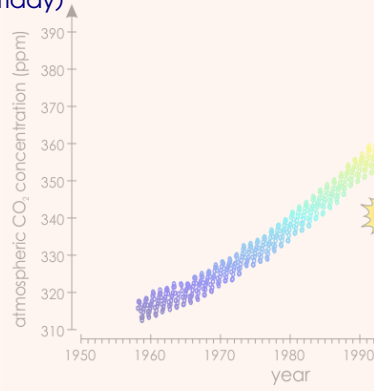
Chapter 10 (continued).

Specific readings

Work plan

i (Wednesday)

ii (Friday)



6. Group project work week

6.1 Specific readings

n/a

6.2 Work plan

6.2.1 i (Wednesday)

(work on group research project)

6.2.2 ii (Friday)

(work on group research project)

Specific readings

Work plan

- i (Wednesday)
- ii (Friday)



7. Paleo biogeochemical worlds I

7.1 Specific readings

- Meyer, K.M., A. Ridgwell, and J.L. Payne, The influence of the biological pump on ocean chemistry: implications for long-term trends in marine redox chemistry, the global carbon cycle, and the evolution of marine animal ecosystems, *Geobiology*, DOI: 10.1111/gbi.12176 (2016).
- Monteiro, F.M., R.D. Pancost, A. Ridgwell, and Y. Donnadieu, Nutrients as the dominant control on the extent of anoxia and euxinia across the Cenomanian-Turonian oceanic anoxic event (OAE2): Model-data comparison, *Paleoceanography*, DOI: 10.1029/2012PA002351 (2012).
- Ridgwell, A., J. Hargreaves, N. Edwards, J. Annan, T. Lenton, R. Marsh, A. Yool, and A. Watson, Marine geochemical data assimilation in an efficient Earth System Model of global biogeochemical cycling, *Biogeosciences* 4, 87-104 (2007).
- Tagliabue, A., O. Aumont, R. DeAth, J.P. Dunne, S. Dutkiewicz, E. Galbraith, K. Misumi, J.K. Moore, A. Ridgwell, E. Sherman, C. Stock, M. Vichi, C. Völker, and A. Yool, How well do global ocean biogeochemistry models simulate dissolved iron distributions?, *GBC*, DOI: 10.1002/2015GB005289 (2016).

7.2 Work plan

7.2.1 i (Wednesday)

(Group presentations.)

7.2.2 ii (Friday)

Marine ecology and biogeochemical cycles in past worlds.



Specific readings

Work plan

i (Wednesday)

ii (Friday)

8. Atmospheric dynamics

8.1 Specific readings

8.2 Work plan

8.2.1 i (Wednesday)

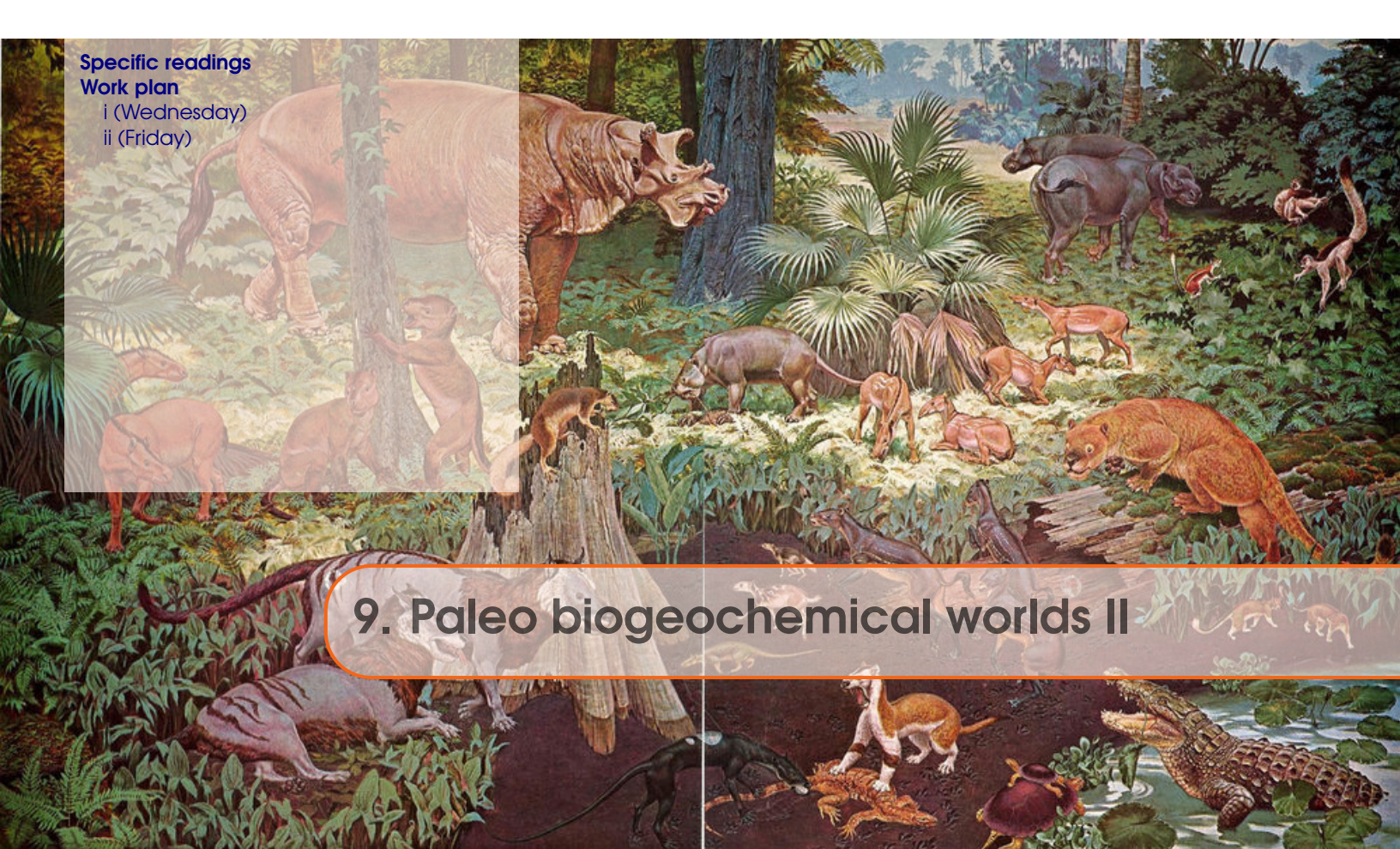
8.2.2 ii (Friday)

Specific readings

Work plan

i (Wednesday)

ii (Friday)



9. Paleo biogeochemical worlds II

9.1 Specific readings

9.2 Work plan

9.2.1 i (Wednesday)

9.2.2 ii (Friday)

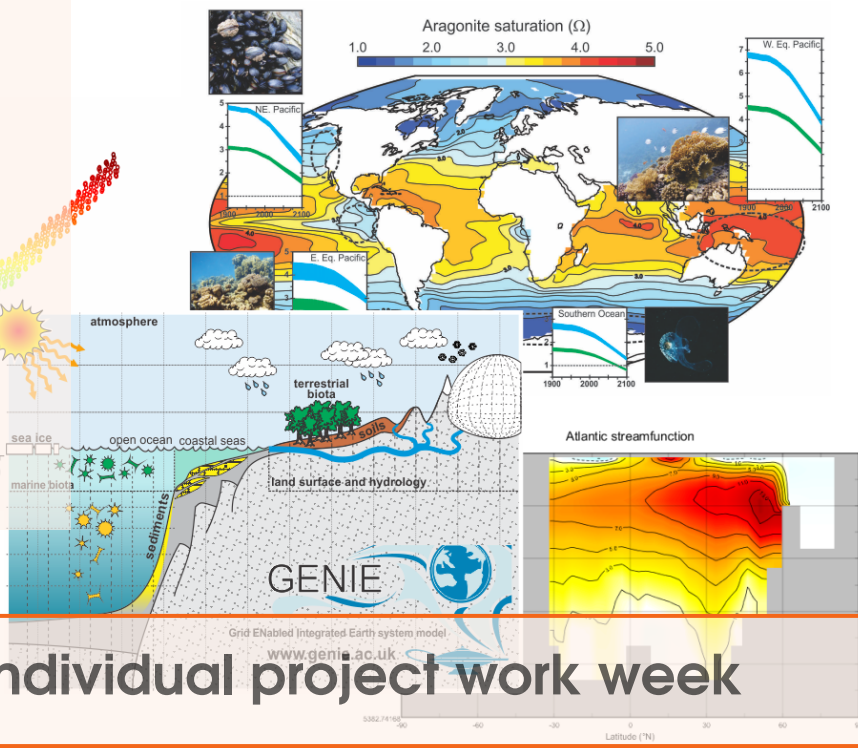
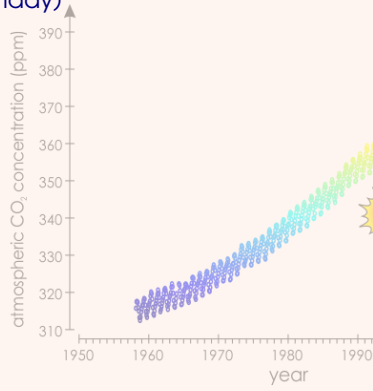
(UCR holiday)

Specific readings

Work plan

i (Wednesday)

ii (Friday)



10. Individual project work week

10.1 Specific readings

n/a

10.2 Work plan

10.2.1 i (Wednesday)

(work on individual research project)

10.2.2 ii (Friday)

(work on individual research project)