



GEO266: An Introduction to Earth system modelling

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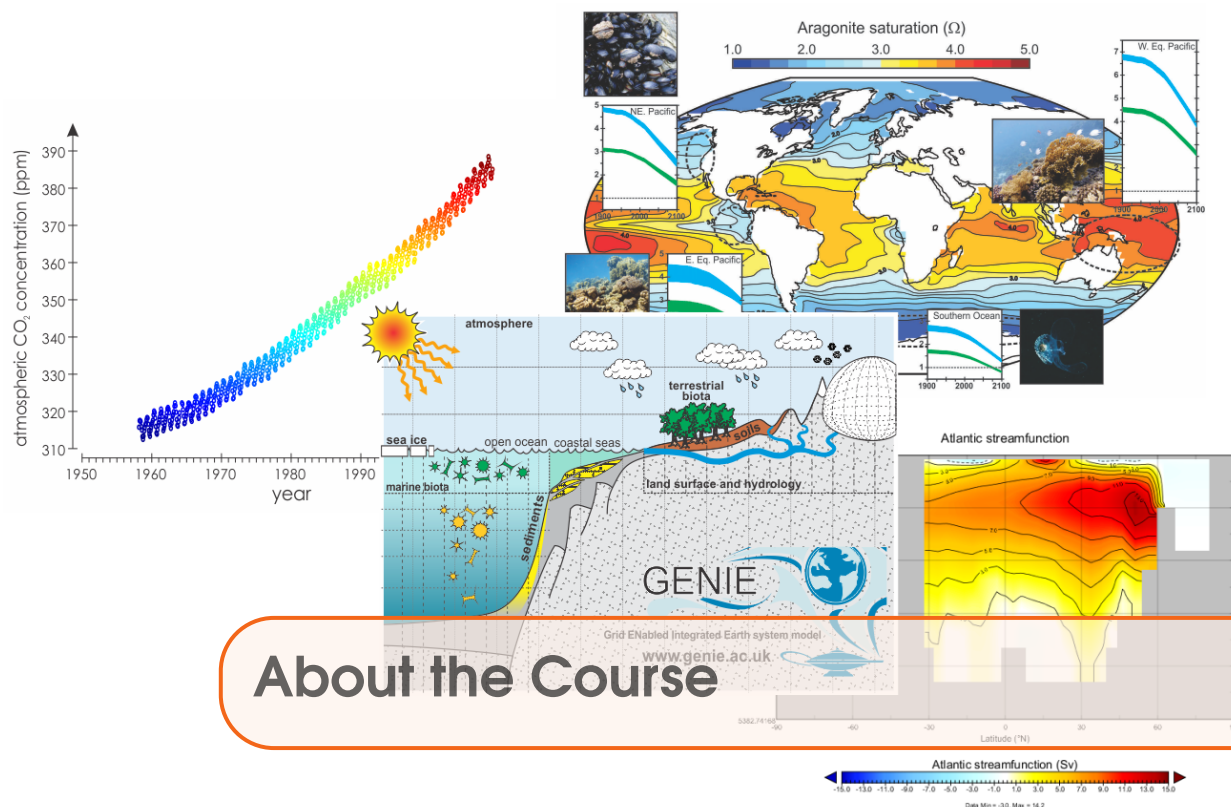
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About the Course

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 functioning of the Earth's climate system as well as of global carbon cycling (and other biogeochemical cycles), including topical issues of past (geological) global change as well as 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 processes underlying the climate system and carbon cycle we see today and infer for the past, 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-line – on Wednesdays from 9:00 am to 11.50 am, and the Lecture/Discussion on Fridays, 9:00 am to 11.50 am. An initial introductory session will be held on Friday 2nd October, and the first full/official class of the course will be on Wednesday 7th October.

Timetable

The timetabling and overall course structure of GEO266 are given in Table 1.

Table 1: Schedule of GEO266

Week #	Wednesday LAB	Friday Discussion/LAB
01 (10/05)	GENIE modelling basics.	snowball Earth!
02 (10/12)	Exploring the nature and dynamics of ocean circulation.	Model data visualization & analysis.
03 (10/19)	CO ₂ emissions, ocean acidification, and climate change.	CO ₂ emissions, ocean acidification, and climate change. (CONTINUED)
04 (10/26)	Nutrient cycling and the ocean's biological pump.	Nutrient cycling and the biological pump. (CONTINUED)
05 (11/02)	Marine ecology.	Marine ecology. (CONTINUED)
06 (11/09)	UCR HOLIDAY (<i>Group project work</i>)	<i>Group project work</i>
07 (11/16)	Group Presentations / The climatology of past & fake worlds.	The climatology of past & fake worlds.
08 (11/23)	Paleoclimate, proxies, and model-data comparison.	UCR HOLIDAY
09 (11/30)	Atmospheric dynamics and coupled (GCM) climate modelling.	GCMs. (CONTINUED)
10 (12/07)	<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, at the end. 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 email¹ questions. Tuesdays or Thursdays (almost any time) would be your best chance of getting any sort of response.

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](#). A draft guide to using this text, specific weekly topics and activities, and assessments, will be provided on the first day of class and updated weekly thereafter.

Course materials

All² course materials will appear on my website – www.seao2.info under the cGENIE.muffin Earth system model tab and in the 'GEO266' box highlighted in **red**:

- The GEO266 course guide/syllabus [PDF file format].
- A copy of an old [example](#) weekly schedule guide from 2019/20.
- The muffin manual (GEO266 course text) [PDF file format].
- Cluster usage rules/guide [plain text format].
- Lecture presentations [PDF file format].

Note that the GEO266 course guide/syllabus and muffin manual will be updated periodically – at least weekly and quite possibly for the muffin manual, daily at times. The revision date of the muffin manual can be found at the bottom of the cover page.

Note that web browsers tend to cache documents, meaning that you may be downloading an 'old' version, even if you have logged out in between ... To force a re-load of the webpage cache in your browser:

- **Windows** – press the Ctrl-F5 key combination.

¹andy@seao2.org

²Including a duplicate copy of the muffin manual PDF.

- **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."

Course technical details

Logistics

The labs are based around using and analysing the ‘**muffin**’ Earth system model³. You 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.

Required software

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

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](#).

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

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

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.)

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 18th December 2020. 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.



0. Introductory session

For this week:

- Ensure that you have the required software installed – see '*Required software*' in this document.
- Read Section 1.1 of the muffin manual (*Before anything else ...*).
- Check that you can log into the domino cluster – Section 1.2.1 (*Logging in!*).
- That's it!
You'll download and test the model code and then start learning how to use the model, next week.

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."

You should see a recent, if not today's date, on the front cover.

1.1 Specific readings

- Snowball Earth reviews:
 - Hoffman and Schrag [2002] (Terra Nova 14, 129-155)
 - Hoffman et al. [2017] (Science Advances 08 Nov 2017: Vol. 3, no. 11, DOI: 10.1126/sci-adv.1600983)
 - Fairchild and Kennedy [2007] (Journal of the Geological Society 2007; v. 164; p. 895-921; doi:10.1144/0016-76492006-191)
- 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 1.2** – Logging in and accessing, configuring, and testing the code.
 In **1.2.1** – Log into your account on `domino.ucr.edu` (via both SSH and SFTP).
 In **1.2.2** – Use `git clone` to get the code.
 (You are doing 'step 1' – *clone*-ing the code.)
 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.
 Then test the code you have installed in **1.2.3**.
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 *base-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)

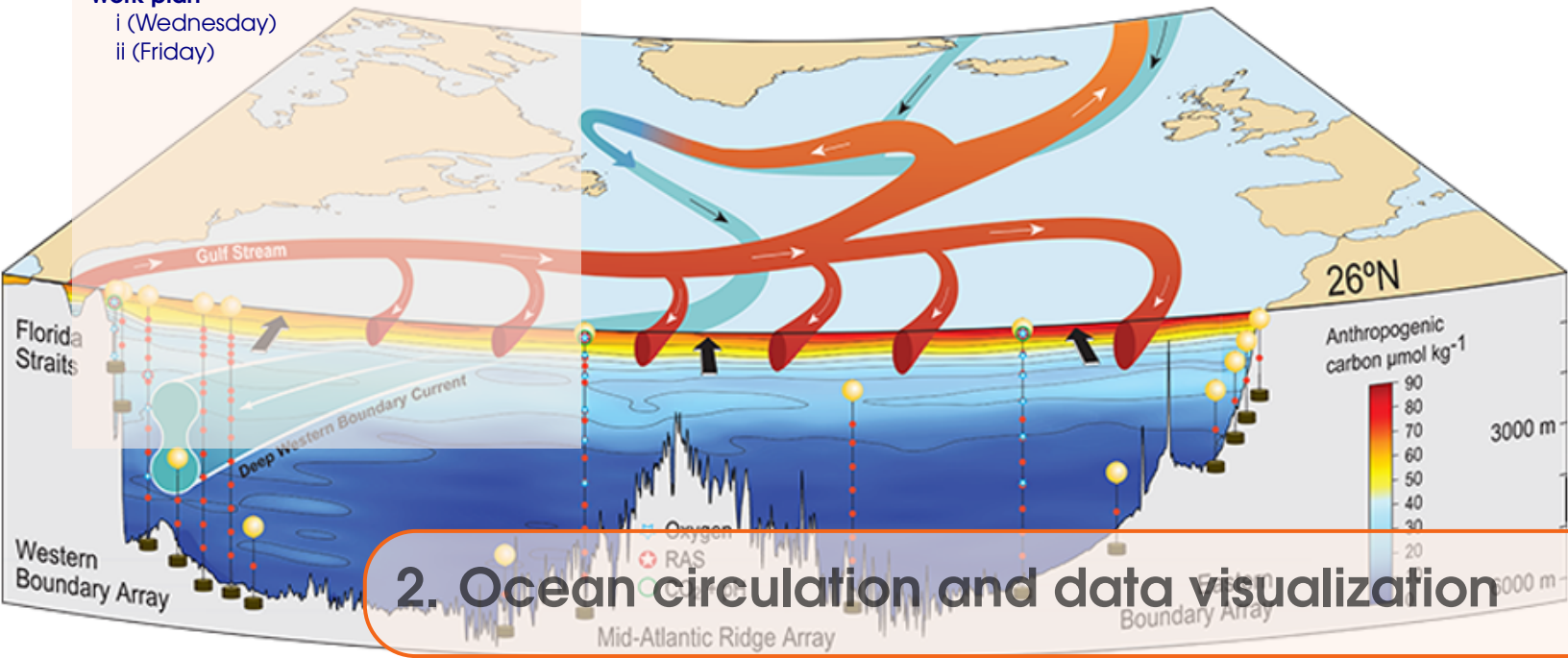
Work through Chapter 2, and specifically:

- Make sure that you read the **Readme** section first!!!
- 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).

Specific readings

Work plan

- i (Wednesday)
- ii (Friday)



2. Ocean circulation and data visualization

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, Pages 745 – 760)
- Characterization of thresholds of AMOC collapse.:
Marsh et al. [2004] (Climate Dynamics, Volume 23, 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:10.1029/2007JG000669)

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)

Firstly – make sure that you have completed the work from Wednesday.

Second – skim through Chapter 14 in the muffin manual to better familiarize yourself with when data output is saved by **muffin**, and what specific data is saved.

Third – skim through Section 15.2 for any further tip re. using **Panopy** that can you pick up.

Forth – look through Section 15.3, concerning plotting in **MATLAB**. You do not have to use **MATLAB** in this course, but it will provide better and more flexible options for plotting and particularly, results processing, later.

If you want to explore some data plotting/processing in MATLAB, first you will need to be able to access the software. If you do not already have it installed on your personal computer:

- **Either:**

On a desktop or laptop, running any of: Windows, MacOS, or linux operating systems, and on which you will install the **MATLAB** software suite. UCR provides you with a free 1-year (renewable) student license. The instructions for obtaining and installing **MATLAB** can be found here:

<https://sitelicense.ucr.edu/matlabstudent.html>

Follow the instructions ... carefully. You will need FIRST to create a (free) account with Mathworks (the **MATLAB** company), then obtain a license key, download and install the software from Mathworks, and then activate the software using the license key you have just obtained. Follow the step-by-step instructions and all should work out A-OK.

- **Or:**

Via any computer and and operating system (including Chromebook) using a web browser – you will log in and connect to a UCR virtual lab ('VLab') and on that virtual machine, run **MATLAB**.

ITS have created an on-line software access system – **Apporto** – UC Riverside's newest virtual computer lab (VLab) service¹. You simply need to visit <http://ucr.apporto.com/> and log in using your UCR NetID credentials to access the app store.

From <http://ucr.apporto.com/>, click on **RDS Apps Full Desktop**. Once booted into the Windows Desktop, you'll see a folder icon for **MATLAB 2020a** – double-click on this to start

¹https://ucrsupport.service-now.com/ucr_portal/?id=kb_article&sys_id=8b5964291b84d49026bd635bbc4bcbd7

MATLAB. (The virtual machine also has Word installed and various other softwares.))

For complete instructions on how to use the new VLab, refer to the link given in the foot-note.

You will probably find installing **MALTA**B on your own desktop/laptop best, but the initial download is large and you'll need several GB of free disk space. Via **Apporto** will work best via a good internet connection, and you'll have to work in the Microsoft Windows operating system (what you may not be familiar with if you generally use a Mac). Via **Apporto** may be advantageous if your internet connection is good but your computer very slow. You can always try both methods and see which one you prefer!

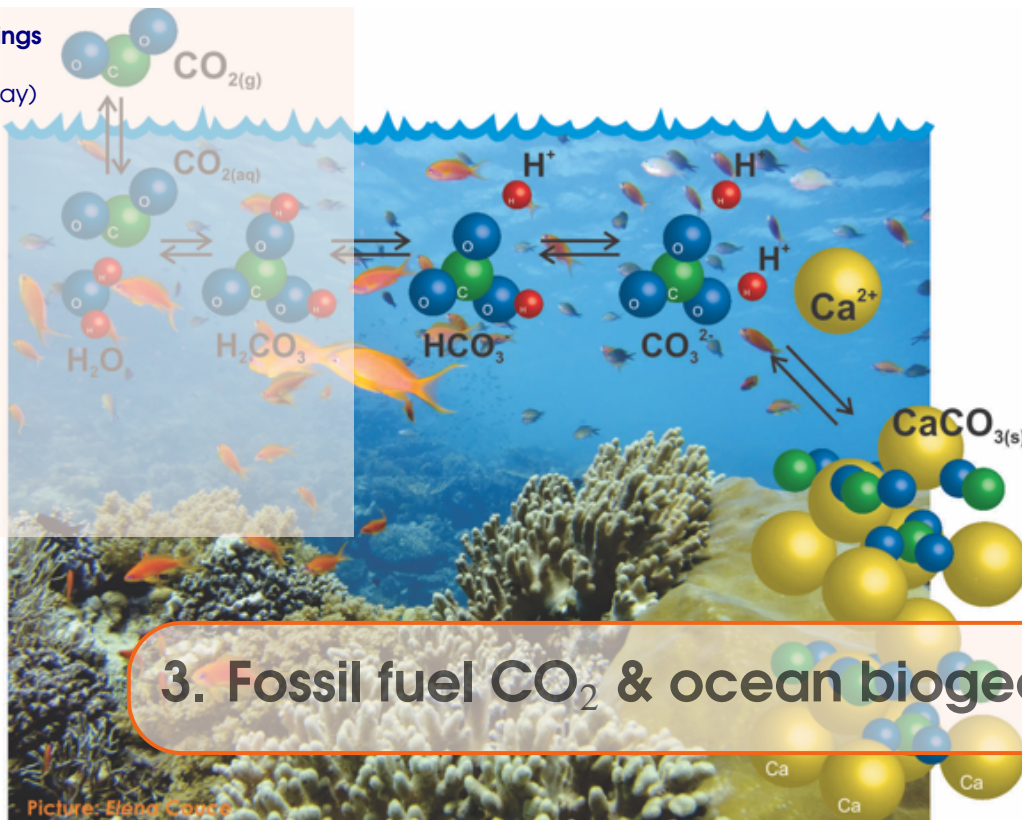
If you have never used **MATLAB** before, Section 15.3.1 points you to some relevant/useful sections in a **MATLAB**/programming text I have developed for GEO111.

Lastly – Chapter 16 provides an over-view of some **MATLAB** programs designed specifically for processing and plotting muffin results.

Specific readings

Work plan

- i (Wednesday)
- ii (Friday)



3.1 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/>

3.2 Work plan

3.2.1 i (Wednesday)

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

3.2.2 ii (Friday)

Keep calm and carry on (emitting carbon).

Specifically: If you are done with the main exercises in 6.1, try out some of the investigations in Section 6.2, and specifically specifically: 6.2.2 (especially, emissions impact on ocean circulation, and diagnosing remaining emissions allowed in order not to exceed a specific atmospheric pCO_2 threshold). You may also be interested in 6.2.4.

4. The ocean's biological pump

4.1 Specific readings

- 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).
<https://www.seao2.info/pubs/bg-4-87-2007.pdf>
- Ridgwell, A., I. Zondervan, J. Hargreaves, J. Bijma, and T. Lenton, Assessing the potential long-term increase of oceanic fossil fuel CO₂ uptake due to 'CO₂-calcification feedback', *Biogeosciences* 4, 481-492 (2007).
<http://www.biogeosciences.net/4/481/2007/bg-4-481-2007.pdf>
- Ridgwell, A., Schmidt, D. N., Turley, C., Brownlee, C., Maldonado, M. T., Tortell, P., and Young, J. R., From laboratory manipulations to Earth system models: scaling calcification impacts of ocean acidification, *Biogeosciences* 6, 2611-2623 (2009).
<http://www.biogeosciences.net/6/2611/2009/bg-6-2611-2009.html>
- Ridgwell, A., and S. Arndt, Why Dissolved Organics Matter: DOC in Ancient Oceans and Past Climate Change, in: *Biogeochemistry of Marine Dissolved Organic Matter* Eds. Hansell, D. A., and C. A. Carlson, Elsevier (2014).
- Kohfeld, K. E., and A. Ridgwell, Glacial-interglacial variability in atmospheric CO₂, in *Surface Ocean–Lower Atmospheres Processes*, Eds. C. Le Quéré and E. S. Saltzman, AGU Geophysical Monograph Series, Volume 187, 350 pp.

4.2 Work plan

4.2.1 i (Wednesday)

Section 7.2 (and read 7.1 and skim through the references).

The exercises are a little less prescribed and more free-form, so read through all of Section 7.2 and then about what you are interested in and would like to do, and plan your experiments and investigations (and how you will analyse them) accordingly. The experiments may also need to be run for longer than you have typically done before (although the (base) configuration is a relatively 'fast' one), and so make use of the cluster queue.

4.2.2 ii (Friday)

Section 7.3.



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. [2018] – 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)

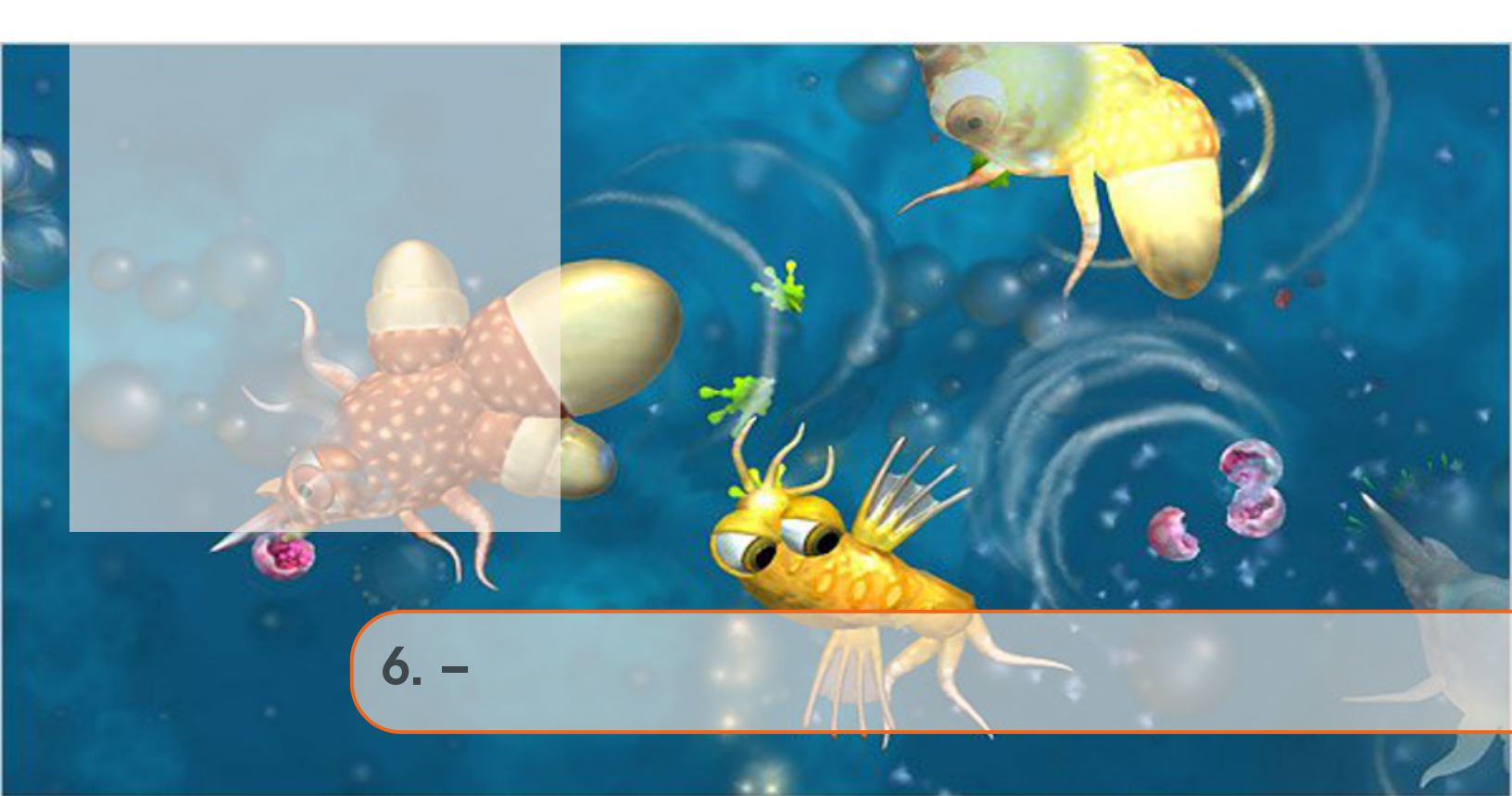
Work through Chapter 8:

- 8.1 – *Getting going with ECOGEM*
- 8.2 – *Ecosystem configuration*
- 8.3 – *Increasing ecological complexity*
- 8.4 – *Build it up, tear it down*

5.2.2 ii (Friday)

- Firstly – carry on working through the Sections you started on Wednesday.

- Secondly – there is a new Section 8.5 with instructions on how to conduct future CO_2 emissions experiments using an ecosystem-equipped configuration of **muffin**.
These are experiments that no-one has done before (or published) as far as I know ... :o)
You will need a code update for some new files, so from the `cgenie.muffin` directory, type:
`git pull`
- Finally ...work on your group project/presentation ideas.



6. -

Work plan

- i (Wednesday)
- ii (Friday) (OPTION 1)
- ii (Friday) (OPTION 2)

7. Past/Alternative Worlds ... sediments

7.1 Work plan

7.1.1 i (Wednesday)

(Group presentations)

7.1.2 ii (Friday) (OPTION 1)

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 generate 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 more 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 to diagnose and understand ocean circulation and climate that you have already learnt.

See Chapter 18.

7.1.3 ii (Friday) (OPTION 2)

Work through chapter 11, particularly 11.1, 11.2, 11.3.

Read:

model description :

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).

Colbourn, G., A. Ridgwell, and T.M. Lenton, The Rock Geochemical Model (RokGeM) v0.9, *Geosci. Model Dev.* 6, 1543-1573, doi:10.5194/gmd-6-1543-2013 (2013).

carbon dynamics :

Lord, N.S., A. Ridgwell, M.C. Thorne, and D.J. Lunt, An impulse response function for the 'long tail' of excess atmospheric CO₂ in an Earth system model, GBC DOI: 10.1002/2014GB005074 (2015).

Archer, D., M. Eby, V. Brovkin, A. Ridgwell, et al., Atmospheric lifetime of fossil-fuel carbon dioxide, *Annual Reviews of Earth and Planetary Sciences* 37, 117-134 (2009).

model applications :

Ridgwell, A., Interpreting transient carbonate compensation depth changes by marine sediment core modeling, *Paleoceanography* 22, PA4102, doi:10.1029/2006PA001372 (2007).

Panchuk, K., A. Ridgwell, and L. R. Kump, Sedimentary response to Paleocene Eocene Thermal Maximum carbon release: A model-data comparison, *Geology* 36, 315-318 (2008).

Chikamoto, M. O., K. Matsumoto, and A. Ridgwell, Response of deep-sea CaCO₃ sedimentation to Atlantic meridional overturning circulation shutdown, *JGR* 113, G03017, doi:10.1029/2007JG000669 (2008).