

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

Lesson #5: Greenhouse climates of the past: the late Cretaceous



Cretaceous forest 120 Million years ago on the Antarctic Peninsula.
Reconstruction based on PhD work of Jodie Howe, University of Leeds/BAS,
painted by Robert Nichols.

Relevant reading:

- Barron, E.: A warm equable Cretaceous: the nature of the problem, *Earth-Science Reviews* **19**, 305–338, 1983.
- Bice, K. L., and R. D. Norris, Possible Atmospheric CO₂ extremes of the middle Cretaceous (late Albian-Turonian), *Paleoceanography* **17**, doi: 10.1029/2002PA000778, 2002.
- Bice, K. L., B. T. Huber, and R. D. Norris, Extreme polar warmth during the Cretaceous greenhouse?: Paradox of the Late Turonian $\delta^{18}\text{O}$ record at DSDP Site 511, *Paleoceanography* **18**, doi: 10.1029/2002PA000848, 2003.
- Bice, K. L., D. Birgel, P. A. Meyers, K. A. Dahl, K. Hinrichs, and R. D. Norris, A multiple proxy and model study of Cretaceous upper ocean temperatures and atmospheric CO₂ concentrations, *Paleoceanography* **21**, PA2002, doi:10.1029/2005PA001203, 2006.
- Donnadieu, Y., et al., Modelling the primary control of paleogeography on Cretaceous climate, *Earth and Planetary Science Letters* **248**, 426–437, 2006.
- Huber, B. T., Norris, R. D., and MacLeod, K. G.: Deep-sea paleotemperature record of extreme warmth during the Cretaceous, *Geology* **30**, 123–126, 2002.
- Hunter, S. J., et al., Modelling Maastrichtian climate: investigating the role of geography, atmospheric CO₂ and vegetation, *Clim. Past Discuss.* **4**, 981–1019, 2008.
- Jenkyns, H. C., Forster, A., Schouten, S., and Sinninghe Damste, J. S.: High temperatures in the Late Cretaceous Arctic Ocean, *Nature* **432**, 888–892, 2004.

0. Readme

- 0.1 You will need to download a new restart file prior to embarking on the experiments with modern ocean circulation.

Change to the `cgenie_output` directory and type (or copy and paste carefully from the PDF ...):

```
$ wget http://www.seao2.info/cgenie/labs/AWI.2017/LAB_5.SPIN.tar.gz
```

This downloads an archived/compressed copy of the 10,000 year spin-up experiment `LAB_5.SPIN`. Extract the contents of this archive by typing:

```
$ tar xfzv LAB_5.SPIN.tar.gz
```

- 0.2 You will also need to carry out a small update of some of the configuration files in the model code. To do this: change directory to the `cgenie.muffin` directory (not `genie-main ... yet ...`) and type:

```
$ svn update
```

Now ... change to `genie-main` directory to run the model.

1. Understanding the climate of the Cretaceous

- 1.0 A previously spun-up state of Maastrichtian climate with cGENIE in a ca. 70 Ma configuration (LAB_5.SPIN) is provided as a starting point. A *user-config* (LAB_5.EXAMPLE) that continues on this climate state is run:

```
$ ./runmuffin.sh cgenie.eb_go_gs_ac_bg.p0067f.NONE LABS
LAB_5.EXAMPLE 10 LAB_5.SPIN
```

(Note that for speed, no carbon cycle is selected in this configuration.)

Your task now is ... 'simple': Account for the Cretaceous reduced Equator-to-pole surface temperature gradient (compared to modern), particularly the apparently much warmer poles. Different data-based time-slices (including the Maastrichtian) are provided in *Huber et al.* [2002], although the low latitude $\delta^{18}\text{O}$ based temperatures are now not considered reliable. *Jenkyns et al.* [2004] contains high latitude (Arctic) data for the Maastrichtian. There are proxy-derived latitudinal temperature gradients and model-data studies for earlier in the Cretaceous – the problem is essentially the same.

The 2-D NetCDF results file contains the surface air temperature field (and sea-ice cover, if any). The 3-D NetCDF results file contains fields for ocean temperatures (and salinity). Both contain continental configuration and ocean bathymetry.

Panoply will plot the zonal average for you (as used in model-data comparisons – e.g., see *Bice and Norris* [2002]) – in the Array(s) tab, the Plot can be set to Zonal Averages rather than Map. You can get a smooth curve by selecting Interpolate. Remember you can set (and fix) scales rather than let Panoply auto-scale continually.

The following 'controls' over the climate system are provided to you in the form of a list of parameters at the bottom of the LAB_5.EXAMPLE *user-config* file for editing:

```
# --- MISC -----
#
# === ATMOSPHERE ===
# CO2 radiative forcing scaling factor [DEFAULT = 4.0]
ea_radfor_scl_co2=4.0
# CH4 radiative forcing scaling factor [DEFAULT = 1.0]
ea_radfor_scl_ch4=1.0
# Equator-to-pole different in planetary albedo [DEFAULT = 0.260]
ea_albedop_amp=0.260
# Baseline planetary albedo [DEFAULT = 0.200]
ea_albedop_offs=0.200
# atmospheric diffusivity of temperature (horizontal) [DEFAULT = 5.0e6]
ea_l2=5.0e6
# === OCEAN ===
# ocean diffusivity of temperature + salinity (horizontal) [DEFAULT = 1494.4]
go_l4=1494.4
# scaling for wind stress (set values of both identical) [DEFAULT = 1.531]
go_l3=1.531
ea_l1=1.531
```

Most of these parameters are associated with the radiative forcing of climate or atmospheric transports. The most useful ones are likely to be:

(i) The line:

```
ea_radfor_scl_co2=4.0
```

which specifies a radiative forcing of climate by CO₂ equivalent to 4 times modern CO₂ (i.e., 4×278 ppm = 1112 ppm) as per before (e.g. snowball Earth experiments). The line:

```
ea_radfor_scl_ch4=1.0
```

specifies a radiative forcing of climate by CH₄ equivalent to 1 times modern CH₄ (i.e., 1×700 ppb). (But effectively, this is going to do exactly the same as changing radiative forcing due to CO₂.)

(ii) cGENIE, as configured here, does not have a land surface scheme (no snow cover) nor clouds nor ice sheets, so a planetary albedo is prescribed (see Figure). This varies with latitude and is parameterized after a fully coupled GCM simulation. There is a parameter which controls how the albedo varies as a function of latitude, which can be adjusted:

```
ea_albedop_amp=0.260
```

However, if you vary this, why are you doing it? (What is the physical justification for giving the poles a higher or lower albedo relative to the Equator?)

There is also a parameter that sets the baseline (minimum) albedo:

```
ea_albedop_offs=0.200
```

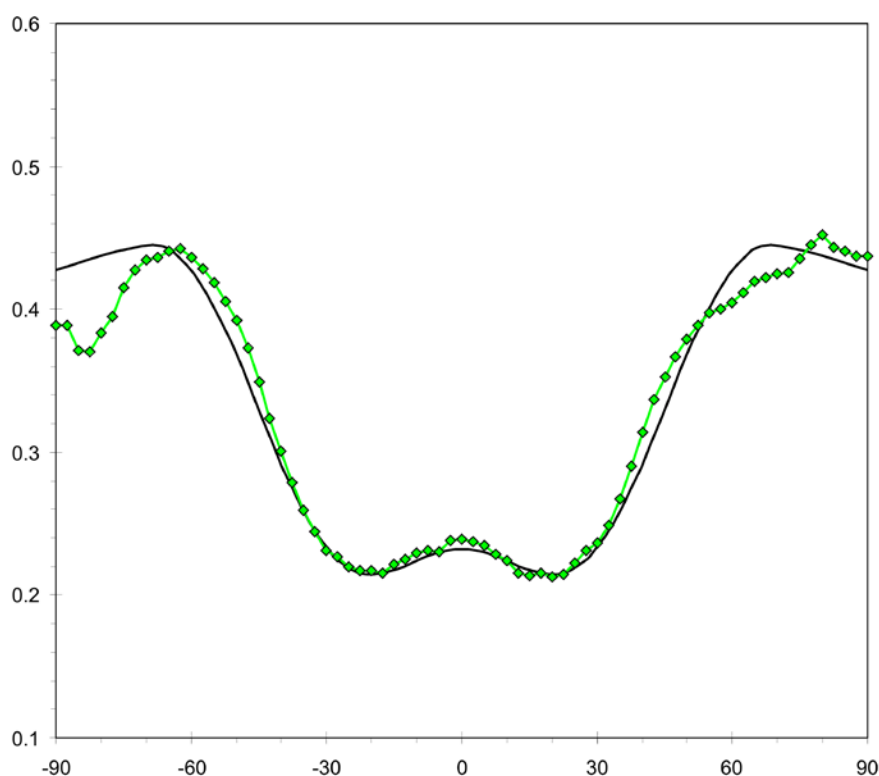
i.e., albedo is primarily a sum of the baseline value plus the Equator-to-pole slope (times the latitude).

(iii) The diffusivity of heat in the atmosphere (since it is a simple 2-D atmospheric model, with no atmospheric circulation, the atmosphere is made 'diffusive' to help capture heat and moisture transport) is:

```
ea_12=5.0e6
```

Note the maximum value the model can cope with is ca. $1.0e7$.

- 1.2 Run the model for however long you think is 'necessary' (/justified). The surface climate will approach equilibrium 'relatively' quickly. Deep ocean temperatures will typically take thousands of years to fully adjust ... You can assess how the model approaches equilibrium most easily from the atmospheric temperature time-series results file, and from the ocean temperature time-series results file (allowing to you to contrast surface and whole ocean temperature changes).



Prescribed planetary albedo.

The latitudinal (from 90°S (-90°N) on the left, to 90°N on the right) profile of planetary albedo as calculated in a fully coupled GCM is given in green, and the cGENIE 'fit' in black.

- 2.0 You can also try tracing and analyzing the patterns of ocean circulation in the Cretaceous world, *in the same way* as you did for the modern climate system. And in fact, it would be a useful exercise to directly compare your previous modern results vs. Cretaceous results, or even better, carry out a set of paired experiments (e.g. similar locations and fluxes of dye injection) for both modern and Cretaceous. (Note that if you do this and swap back and forth between modern and Cretaceous configurations, you cannot submit straight away to the cluster but must first briefly run the experiment at the command line in order that cGENIE is compiled into the new continental configuration.) A new *user-config* (LAB_5. colorinjection) that continues on this climate state is run:

```
$ ./runmuffin.sh cgenie.eb_go_gs_ac_bg.p0067f.rb LABS  
LAB_5.colorinjection 10 LAB_5.SPIN
```

(Also note that the *base-config* is different as it now includes the definition of 2 dye tracers.)

The default locations for the dye release are set different compared to in the modern configuration (LAB 2). BUT, the default location is not necessarily ideal / particularly revealing ... so you'll need to look count grid cells West-to-East (the *i* direction) and from South to North (the *j* direction) in order to determine a more suitable location for tracing circulation.

By means of dye tracing, looking at the (global only) overturning stream-function, and/or temperature and salinity (and density) profiles, see if you can identify where in the Cretaceous ocean deep water forms in the model. AND, more importantly, think about WHY does it form where it does?

Also: what about surface ocean circulation and gyres? Are these located where you would expect (e.g. based on your understanding of modern ocean circulation). Plot velocity vectors to help, and/or refer to the Barotropic streamfunction output in the 2D netCDF file.