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

VI: Late Cretaceous sea surface temperatures and carbon cycling

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 CO_2 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 $\delta^{18}O$ 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 CO_2 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 CO_2 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.

16. Understanding the climate of the Cretaceous (and Palaeogene)

16.1 A previously spun-up state of Maastrichtian climate with GENIE in a ca. 70 Ma configuration (exp0_Cretaceous_SPINUP) is provided as a starting point:

```
$ ./runcgenie.sh cgenie_eb_go_gs_ac_bg.p0067f.NONE LABS
  exp11_Cretaceous 10 exp0_Cretaceous_SPINUP
```

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

Your task now is ... 'simple' (lol): 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 $\delta^{18}O$ 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 (e.g., by Karen Bice) 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 parameter that you can edit the value of. In the exp11_Cretaceous *user-config*:

```
# --- ADDITIONAL -----------------------------------------
#
# === 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_12=5.0e6
# === OCEAN ===
# ocean diffusivity of temperature + salinity (horizontal) [DEFAULT = 1494.4]
go_14=1494.4
# scaling for wind stress (set values of both identical) [DEFAULT = 1.531]
go_13=1.531
ea_11=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 CO_2 equivalent to 4 times modern CO_2 (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 CH_4 equivalent to 1 times modern CH_4 (i.e., 1×700 ppb).

(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`.

16.2   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).
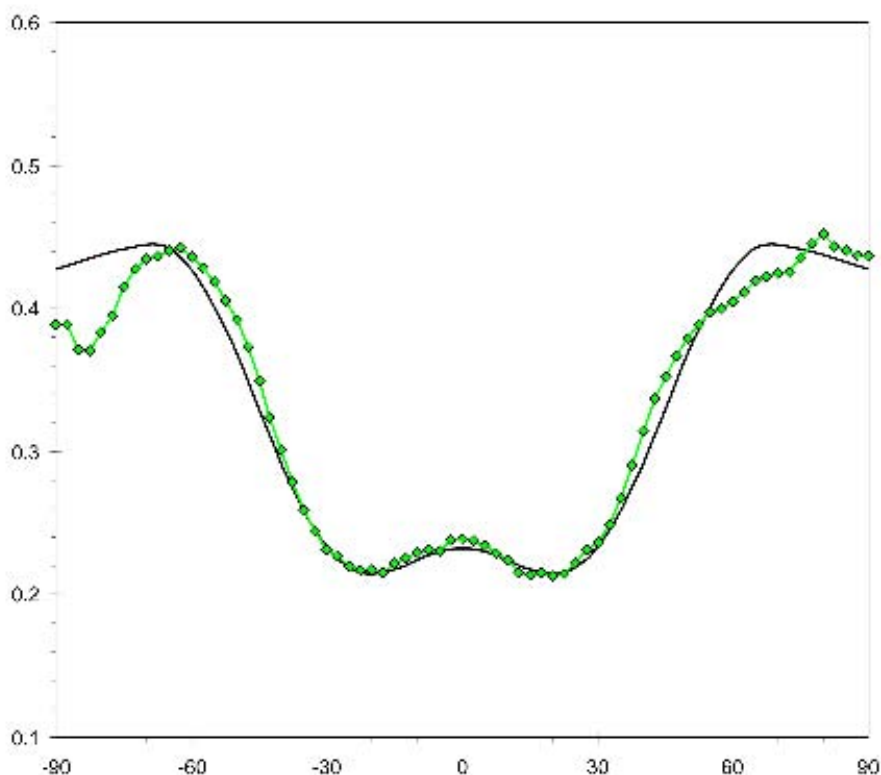
Prescribed planetary albedo.
The latitudinal (from 90°S (-90°N) on the left, to 90°N on the right) profile of planetary albedo as calculated in a fully coupled GCM is given in green, and the *c*GENIE 'fit' in black.

17. Cretaceous carbon cycling

17.1 A previously spun-up state of Maastrichtian climate with GENIE in a ca. 70 Ma configuration but now with an ocean carbon cycle, (`exp0_CretaceousALT_SPINUP`) is provided, e.g.:

```
$ ./runcgenie.sh cgenie_eb_go_gs_ac_bg.p0067f.BASESCH4 LABS
  exp11_CretaceousALT 10 exp0_CretaceousALT_SPINUP
```

Start by exploring some of the ocean biogeochemical fields, both horizontal sections and vertical slices, such as nutrient (PO_4) distributions (and surface productivity distributions), and $\delta^{13}C$ as a key paleo tracer of biogeochemical cycling, and perhaps dissolved O_2 (a good indicator of both biological productivity and ocean circulation but with a poor proxy representation except in extreme (e.g. black shale) settings).

17.2 Try adjusting the biological pump in the ocean. Some of the relevant parameter values are the same as in Section **vb** (Glacial CO_2) such as remineralization depth-scale (and recalcitrant fraction) of organic matter. For biological uptake, `bg_par_bio_k0_PO4` (default value: `8.9876e-006`) is the controlling parameter in this biological configuration (there is no Fe cycle or limitation of productivity).

You can also change the inventory of PO_4 in the ocean. E.g. to add 1 µmol kg-1 of PO_4 uniformly to the ocean (doubling the default), to the experiment *user-config*, add the line:

`bg_ocn_dinit_8=1.0E-6`

(Note that adjusting the ocean PO4 inventory should only be done once and not accidentally in each successive experiment …)