Data README for
"Simulation data for tracing snowball bifurcation on an earth-like aquaplanet over 4 billion years"
V 2022-07-27

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and also the article for which this data are supplementary material:
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Update 2023-03-10: For the revised version of the submitted paper, the plot script `threshold_paper_public.i` for the figures was updated, and accordingly the description of the figures in this Readme. Neither input data nor output data were changed.

Contents

Abstract

The atmospheric concentration of CO_2 at which global glaciation (snowball) bifurcation occurs, changes throughout Earth's history, most notably because of the slowly increasing solar luminosity. Quantifying this critical CO_2 concentration is not only interesting from a climate dynamics perspective, but also an important prerequisite for understanding past Snowball Earth episodes as well as the conditions for habitability on Earth and other planets. Here we use the coupled climate model CLIMBER-3α in an Aquaplanet configuration to scan for the Snowball bifurcation point for time slices spanning the last 4 billion years, thus quantifying the time evolution of the bifurcation and identifying a qualitative shift in critical state dynamics.

CLIMBER-3α is a relatively fast Earth-system model of intermediate complexity, which allows us to scan a total of 18 time slices throughout Earth's history. It consists of a modified version of the ocean general circulation model (OGCM) MOM3 with a horizontal resolution of 3.75° x 3.75° and 24 vertical levels, a dynamic/thermodynamic sea-ice model at the same horizontal resolution and a fast statistical-dynamical atmosphere model with a coarse horizontal resolution of 22.5° in longitude and 7.5° in latitude. The sea-ice model explicitly takes into account sea-ice dynamics, a factor which has been found to be of crucial importance for the Snowball bifurcation. The effects of snow cover on sea ice are explicitly taken into account. The main limitations of the model relate to its simplified atmosphere component. For more details see the corresponding paper Feulner et al. (2022b).

The data presented here is the model output on which the results described in the corresponding manuscript are based on. The model output is provided in different netcdf files. The structure of the model output is explained in this Readme file (Part 1). Additionally, the generation of the model input data is described and the figures of the publication, and scripts to analyse the model output and generate the figures are contained (Part 2).

Part 1: Description of model output data

The Snowball bifurcation point is derived for a total of 18 time slices ranging from today to 3600 Ma (million years ago), see Table 1 in Feulner et al. (2022b).

Each run's name gives relevant information about the parameter setting:

Example: `c3beta_aqua_3300Ma_52000ppm`

c3beta model version

aqua aquaplanet topography

3300Ma time slice, corresponding to a specific value for the solar constant

52000ppm atmospheric CO_2 concentration was set to 52000 ppm

In addition, we have run model experiments at two fixed levels of CO_2 (10,000 ppm and 10 ppm) and variied solar luminosity (in W/m^2). These runs are named like `c3beta_aqua_00010ppm_1324Wm2`

Some runs have name suffixes, e.g.:
`-6h` : The model timestep was shortened 6h to overcome numerical instabilities.
`_three` : Just a name for internal bookkeeping (the 3rd attempt to perform a run with these settings :-).
`c3beta_aqua_0900Ma_00230ppm` vs. `c3beta_aqua_0900Ma_00230ppm_constCO2` : For the run without the name suffix, CO_2 forcing was stepwise reduced until the snowball bifurcation point was reached. As countercheck, the run with name suffix `_constCO2` was configured with constant CO_2 forcing from its initial conditions on.
`c3beta_aqua_1500Ma_01170ppm_from_1180ppm` vs. `c3beta_aqua_1500Ma_01170ppm_from_1200ppm` : Also two runs with different approach of CO_2 forcing to the desired 1200 ppm level.

Model output

Most relevant files:

`topog.dta.nc` describes the aquaplanet topography and grid cells. As explained in the paper, it is the same for all runs.

history files contain yearly values of the variables for each model year the simulation was run.

Ocean model data:	`history.nc`
Atmosphere model data:	`history_potsdam2.nc`
Sea-ice model data:	`history_isis.nc`

snapshots contain monthly values of the variables for the model year **before** the one given in the name.

Ocean model data:	`snapshots.00....01.01.dta.nc`
Atmosphere model data:	`snapshots_potsdam2.00....01.01.dta.nc`
Sea-ice model data:	`snapshots_isis.00....01.01.dta.nc`

Part 2: Description of files for creating input data, figures etc

Preprocessing

Preprocessing of model input files was done with `Yorick` (`http://yorick.sourceforge.net/`, version 2.2.04). The preprocessing function `glac_proc_topo` used to generate the topography input files for the aquaplanet simulations can be found in the script `threshold_paper_public.i` in directory

`PrePostProcessing/`,

the generated output files in directory

`PrePostProcessing/ModelInput/`.

Postprocessing

Postprocessing of model output files was done with `Yorick` (`http://yorick.sourceforge.net/`, version 2.2.04) and `cdo`. `Yorick` postprocessing functions can be found in the script `threshold_paper_public.i` in directory

`PrePostProcessing/`,

the generated output files in directory

`PrePostProcessing/ModelOutput/`.

The relevant data files in this directory include

`snowball_bifurcation_aquaplanet_final.dat` : Lists time slice, solar constant as well as the CO_2 concentrations of the snowball and critical states, respectively. Generated by hand based on model simulations for the individual time slices. Used to generate Figure 1 in the paper.

`critical_states_characteristics.dat` : Generated by the function `glac_diag_critical_states_global` in `threshold_paper_public.i`. Reads `snowball_bifurcation_aquaplanet_final.dat` as well as the atmosphere and sea-ice history files of the critical states. Primarily used to generate Figure 2 in the paper, implicitly also for Figure 3.

`0900Ma_states_characteristics.dat` : Generated by the function `glac_diag_900Ma_states` in `threshold_paper_public.i` . Reads the atmosphere and sea-ice history files of the 900 Ma equilibrium states. Used to generate Figure 3 in the paper.

`hadley_states_characteristics.dat` : Generated by the function `glac_diag_hadley_states` . Reads `snowball_bifurcation_aquaplanet_final.dat` , `critical_states_characteristics.dat` as well as the global and annual mean sea-ice fraction from the `history_isis_mean.nc` files. These files have been created using

```
cdo fldmean history_isis.nc history_isis_mean.nc
```

in the directories of the stable and transient Hadley states. Primarily used to compute the length of transient Hadley states quoted in the paper and to create Figure 4.

The 3000 Ma and 900 Ma states are used as example critical states for Ferrel states and Hadley states, respectively, in particular for Figures 5 and 6. The files:

`3000Ma_32600ppm_history_p2.ts_ann.timmean.nc`,
`3000Ma_32600ppm_history_isis.con_g.timmean.nc`
`3000Ma_32600ppm_snapshots_potsdam2.timmean.nc`
`0900Ma_00240ppm_history_p2.ts_ann.timmean.nc`
`0900Ma_00240ppm_history_isis.con_g.timmean.nc` and
`0900Ma_00240ppm_snapshots_potsdam2.timmean.nc`

have been created using `cdo` in the following manner (including additional files for the individual `cdo`-postprocessing steps originally intended for further analysis which were not used in the end):

3000 Ma, 32600 ppm:

```
cdo seltimestep,7503/7602 history_p2.nc history_p2.last100years.nc
cdo selname,ts_ann history_p2.last100years.nc history_p2.ts_ann.last100years.nc
cdo timmean history_p2.ts_ann.last100years.nc history_p2.ts_ann.timmean.nc

cdo seltimestep,7503/7602 history_isis.nc history_isis.last100years.nc
cdo selname,con_g history_isis.last100years.nc history_isis.con_g.last100years.nc
cdo timmean history_isis.con_g.last100years.nc history_isis.con_g.timmean.nc

cdo timmean -cat 'snapshots_potsdam2.007[56]*' snapshots_potsdam2.timmean.nc
```

900 Ma, 240 ppm:

```
cdo seltimestep,3503/3602 history_p2.nc history_p2.last100years.nc
cdo selname,ts_ann history_p2.last100years.nc history_p2.ts_ann.last100years.nc
cdo timmean history_p2.ts_ann.last100years.nc history_p2.ts_ann.timmean.nc

cdo seltimestep,3503/3602 history_isis.nc history_isis.last100years.nc
cdo selname,con_g history_isis.last100years.nc history_isis.con_g.last100years.nc
cdo timmean history_isis.con_g.last100years.nc history_isis.con_g.timmean.nc

cdo timmean \
    -cat 'snapshots_potsdam2.00350[4-9]* snapshots_potsdam2.0035[1-9]* snapshots_potsdam2.0036*' \
   snapshots_potsdam2.timmean.nc
```

For all the other Hadley states in addition to the 900 Ma state, the aggregated atmosphere snapshot files are needed for the EBM analysis shown in Figure 8. These files have been created using `cdo` in the following manner:

```
cdo timmean \
    -cat 'snapshots_potsdam2.00560[2-9]* snapshots_potsdam2.0056[1-9]* snapshots_potsdam2.0057*' \
    0000Ma_00000p1ppm_snapshots_potsdam2.timmean.nc

cdo timmean \
    -cat 'snapshots_potsdam2.00400[2-9]* snapshots_potsdam2.0040[1-9]* snapshots_potsdam2.0041*' \
    0150Ma_00003ppm_snapshots_potsdam2.timmean.nc

cdo timmean \
    -cat 'snapshots_potsdam2.00200[3-9]* snapshots_potsdam2.0020[1-9]* snapshots_potsdam2.0021*' \
```

```
    0300Ma_00011ppm_snapshots_potsdam2.timmean.nc
cdo timmean \
    -cat 'snapshots_potsdam2.00600[2-9]* snapshots_potsdam2.0060[1-9]* snapshots_potsdam2.0061*' \
    0500Ma_00045ppm_snapshots_potsdam2.timmean.nc
cdo timmean \
    -cat 'snapshots_potsdam2.00250[3-9]* snapshots_potsdam2.0025[1-9]* snapshots_potsdam2.0026*' \
    0700Ma_00100ppm_snapshots_potsdam2.timmean.nc
cdo timmean \
    -cat 'snapshots_potsdam2.00350[4-9]* snapshots_potsdam2.0035[1-9]* snapshots_potsdam2.0036*' \
    0900_00240ppm_snapshots_potsdam2.timmean.nc
cdo timmean \
    -cat 'snapshots_potsdam2.00250[2-9]* snapshots_potsdam2.0025[1-9]* snapshots_potsdam2.0026*' \
    1050Ma_00380ppm_snapshots_potsdam2.timmean.nc
cdo timmean \
    -cat 'snapshots_potsdam2.00663[2-9]* snapshots_potsdam2.0066[4-9]* snapshots_potsdam2.0067*' \
    1200Ma_00570ppm_snapshots_potsdam2.timmean.nc
cdo timmean \
    -cat 'snapshots_potsdam2.00553[5-9]* snapshots_potsdam2.0055[4-9]* snapshots_potsdam2.0056*' \
    1800Ma_02620ppm_snapshots_potsdam2.timmean.nc
```


Analysis of model output

The `Yorick` (`http://yorick.sourceforge.net/`, version 2.2.04) script `threshold_paper_public.i` used to create figures of the publication and to calculate certain values can be found in directory

`Postprocessing/.`

The corresponding functions are called `glac_figure1`, `glac_figure2`, `glac_figure3`, `glac_figure4`, `glac_figure5ac`, `glac_figure5bd`, `glac_figure6`, `glac_figure7` and `glac_figure8`.

Figure descriptions:

Figure 1: Snowball bifurcation (in terms of CO_2 partial pressure assuming 1 bar total atmospheric pressure) as a function of solar luminosity for the Aquaplanet simulations.

Figure 2: (a) Global annual mean surface air temperature and (b) sea-ice fraction of critical states as a function of solar luminosity.

Figure 3: Global and annual mean sea-ice fraction in equilibrium climate states at 900 Ma for various concentrations of atmospheric CO_2.

Figure 4: Transient Hadley states with a global mean sea-ice cover of about 50 % in simulations on track to a Snowball.

Figure 5: Maps of annual mean surface air temperatures (left-hand panels a,c) and sea-ice fractions (right-hand panels b,d) for the critical states at 3000 Ma (upper panels a,b) and 900 Ma (lower panels c,d). Only one quarter of the globe is displayed in each map since the Aquaplanet simulations exhibit a high degree of symmetry. Surface wind velocity vectors are shown in the right-hand panels, with the length scaling for a wind speed of 10 m/s indicated in the bottom right corner.

Figure 6: Zonal means of (a) annual mean surface air temperatures, (b) sea-ice fractions, and (c) meridional wind speed for the Ferrel state at 3000 Ma and the Hadley state at 900 Ma.

Figure 7: Schematic illustration of the differences between the critical states (a) at lower solar luminosities ("Ferrel states") and (b) at higher solar luminosities ("Hadley states").

Ferrel 8: (a) Total difference of zonally averaged surface temperatures as diagnosed using a one-dimensional energy balance equation between the Hadley states from 1800 Ma to 0 Ma and the one at 900 Ma. The other panels show the contributions of changes in absorbed solar radiation (b), greenhouse warming (c), and the combined atmospheric and oceanic meridional heat transport (d).

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