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

`https://doi.org/10.5880/pik.2022.003`

Georg Feulner

Potsdam Institute for Climate Impact Research, Member of the Leibniz Association, Potsdam, Germany

Mona Sofie Bukenberger

Potsdam Institute for Climate Impact Research, Member of the Leibniz Association, Potsdam, Germany;
Institute for Atmospheric and Climate Science, ETH Zürich, Switzerland

Stefan Petri

Potsdam Institute for Climate Impact Research, Member of the Leibniz Association, Potsdam, Germany

Contact person: Georg Feulner <`feulner@pik-potsdam.de`>

License

Citation

When using the data please cite:
G. Feulner, M. S. Bukenberger, and S. Petri. Simulation data for tracing snowball bifurcation on an earth-like aquaplanet over 4 billion years. Scientific Data Set, V 2022-07-27. GFZ Data Services, July 2022. doi:10.5880/PIK.2022.003, `https://doi.org/10.5880/PIK.2022.003`

and also the article for which this data are supplementary material:
G. Feulner, M. Bukenberger, and S. Petri. Tracing the Snowball bifurcation of Aquaplanets through time reveals a fundamental shift in critical-state dynamics. *Earth System Dynamics*, 14(3):533–547, May 2023. doi: 10.5194/esd-14-533-2023. `https://doi.org/10.5194/esd-14-533-2023`

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 $3.75° \times 3.75°$ 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. (2023).

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. (2023).

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).

References

Y. Abe, A. Abe-Ouchi, N. H. Sleep, and K. J. Zahnle. Habitable Zone Limits for Dry Planets. *Astrobiology*, 11(5):443–460, June 2011. doi: 10.1089/ast.2010.0545.

J. Bendtsen. Climate sensitivity to changes in solar insolation in a simple coupled climate model. *Climate Dynamics*, 18(7): 595–609, Jan. 2002. doi: 10.1007/s00382-001-0198-4.

A. Bonanno, H. Schlattl, and L. Paternò. The age of the Sun and the relativistic corrections in the EOS. *Astron. Astrophys.*, 390: 1115–1118, Aug. 2002. doi: 10.1051/0004-6361:20020749.

M. I. Budyko. The effect of solar radiation variations on the climate of the earth. *Tellus*, 21:611–619, 1969. doi: 10.1111/j. 2153-3490.1969.tb00466.x.

R. F. Cahalan and G. R. North. A Stability Theorem for Energy-Balance Climate Models. *Journal of Atmospheric Sciences*, 36 (7):1178–1188, July 1979. doi: 10.1175/1520-0469(1979)036<1178:ASTFEB>2.0.CO;2.

M. A. Chandler and L. E. Sohl. Climate forcings and the initiation of low-latitude ice sheets during the Neoproterozoic Varanger glacial interval. *J. Geophys. Res.*, 105(D16):20737–20756, Jan. 2000. doi: 10.1029/2000JD900221.

B. Charnay, F. Forget, R. Wordsworth, J. Leconte, E. Millour, F. Codron, and A. Spiga. Exploring the faint young Sun problem and the possible climates of the Archean Earth with a 3-D GCM. *J. Geophys. Res.*, 118(D17):10414–10431, Sept. 2013. doi: 10.1002/jgrd.50808.

B. Charnay, E. T. Wolf, B. Marty, and F. Forget. Is the Faint Young Sun Problem for Earth Solved? *Space Sci. Rev.*, 216(5):90, July 2020. doi: 10.1007/s11214-020-00711-9.

M. Claussen, L. A. Mysak, A. J. Weaver, M. Crucifix, T. Fichefet, M.-F. Loutre, S. L. Weber, J. Alcamo, V. A. Alexeev, A. Berger, R. Calov, A. Ganopolski, H. Goosse, G. Lohmann, F. Lunkeit, I. I. Mokhov, V. Petoukhov, P. Stone, and Z. Wang. Earth system models of intermediate complexity: closing the gap in the spectrum of climate system models. *Climate Dynamics*, 18: 579–586, Feb. 2002. doi: 10.1007/s00382-001-0200-1.

Y. Donnadieu, G. Ramstein, F. Fluteau, D. Roche, and A. Ganopolski. The impact of atmospheric and oceanic heat transports on the sea-ice-albedo instability during the Neoproterozoic. *Climate Dynamics*, 22:293–306, 2004. doi: 10.1007/s00382-003-0378-5.

P. G. Drazin and D. H. Griffel. On the Branching Structure of Diffusive Climatological Models. *Journal of Atmospheric Sciences*, 34(11):1696–1706, Nov. 1977. doi: 10.1175/1520-0469(1977)034<1696:OTBSOD>2.0.CO;2.

S. G. Driese, M. A. Jirsa, M. Ren, S. L. Brantley, N. D. Sheldon, D. Parker, and M. Schmitz. Neoarchean paleoweathering of tonalite and metabasalt: Implications for reconstructions of 2.69 Ga early terrestrial ecosystems and paleoatmospheric chemistry. *Precambrian Res.*, 189(1-2):1–17, 2011. doi: 10.1016/j.precamres.2011.04.003.

A. Faegre. An Intransitive Model of the Earth-Atmosphere-Ocean System. *Journal of Applied Meteorology*, 11(1):4–6, Feb. 1972. doi: 10.1175/1520-0450(1972)011<0004:AIMOTE>2.0.CO;2.

G. Feulner. The faint young sun problem. *Rev. Geophys.*, 50:RG2006, 2012. ISSN 8755-1209. doi: 10.1029/2011RG000375.

G. Feulner. Formation of most of our coal brought Earth close to global glaciation. *Proc. Natl. Acad. Sci.*, 114(43):11333–11337, Oct. 2017. doi: 10.1073/pnas.1712062114.

G. Feulner and H. Kienert. Climate simulations of Neoproterozoic snowball Earth events: Similar critical carbon dioxide levels for the Sturtian and Marinoan glaciations. *Earth Planet. Sc. Lett.*, 404:200–205, 2014. doi: 10.1016/j.epsl.2014.08.001.

G. Feulner, C. Hallmann, and H. Kienert. Snowball cooling after algal rise. *Nature Geosci.*, 8:659–662, Sept. 2015. doi: 10.1038/ngeo2523.

G. Feulner, M. S. Bukenberger, and S. Petri. Simulation data for tracing snowball bifurcation on an earth-like aquaplanet over 4 billion years. Scientific Data Set, V 2022-07-27. GFZ Data Services, July 2022. doi:10.5880/PIK.2022.003, `https://doi.org/10.5880/PIK.2022.003`.

G. Feulner, M. Bukenberger, and S. Petri. Tracing the Snowball bifurcation of Aquaplanets through time reveals a fundamental shift in critical-state dynamics. *Earth System Dynamics*, 14(3):533–547, May 2023. doi: 10.5194/esd-14-533-2023. `https://doi.org/10.5194/esd-14-533-2023`.

T. Fichefet and M. A. Morales Maqueda. Sensitivity of a global sea ice model to the treatment of ice thermodynamics and dynamics. *J. Geophys. Res. - Oceans*, 102(C6):12609–12646, June 1997. doi: 10.1029/97JC00480.

R. P. Fiorella and N. D. Sheldon. Equable end Mesoproterozoic climate in the absence of high CO_2. *Geology*, 45(3):231–234, Mar. 2017. doi: 10.1130/G38682.1.

G. L. Foster, D. L. Royer, and D. J. Lunt. Future climate forcing potentially without precedent in the last 420 million years. *Nature Communications*, 8:14845, Apr. 2017. doi: 10.1038/ncomms14845.

D. M. W. Frierson, J. Lu, and G. Chen. Width of the Hadley cell in simple and comprehensive general circulation models. *Geophys. Res. Lett.*, 34(18):L18804, Sept. 2007. doi: 10.1029/2007GL031115.

T. Gal-Chen and S. H. Schneider. Energy balance climate modeling: Comparison of radiative and dynamic feedback mechanisms. *Tellus*, 28(2):108–121, Jan. 1976. doi: 10.3402/tellusa.v28i2.10261.

M. Ghil. Climate Stability for a Sellers-Type Model. *Journal of Atmospheric Sciences*, 33(1):3–20, Jan. 1976. doi: 10.1175/1520-0469(1976)033<0003:CSFAST>2.0.CO;2.

D. O. Gough. Solar interior structure and luminosity variations. *Sol. Phys.*, 74:21–34, Nov. 1981. doi: 10.1007/BF00151270.

M. Heinemann, J. H. Jungclaus, and J. Marotzke. Warm Paleocene/Eocene climate as simulated in ECHAM5/MPI-OM. *Climate of the Past*, 5(4):785–802, Dec. 2009. doi: 10.5194/cp-5-785-2009.

I. M. Held and M. J. Suarez. Simple albedo feedback models of the icecaps. *Tellus*, 26(6):613–629, Jan. 1974. doi: 10.3402/tellusa.v26i6.9870.

A. M. Hessler, D. R. Lowe, R. L. Jones, and D. K. Bird. A lower limit for atmospheric carbon dioxide levels 3.2 billion years ago. *Nature*, 428:736–738, Apr. 2004. doi: 10.1038/nature02471.

P. F. Hoffman and D. P. Schrag. The snowball Earth hypothesis: testing the limits of global change. *Terra Nova*, 14:129–155, 2002. doi: 10.1046/j.1365-3121.2002.00408.x.

M. Hofmann and M. A. Morales Maqueda. Performance of a second-order moments advection scheme in an Ocean General Circulation Model. *J. Geophys. Res.*, 111(C5):C05006, May 2006. doi: 10.1029/2005JC003279.

J. Huang and K. P. Bowman. The small ice cap instability in seasonal energy balance models. *Climate Dynamics*, 7(4):205–215, June 1992. doi: 10.1007/BF00206862.

Y. Huang and M. Bani Shahabadi. Why logarithmic? A note on the dependence of radiative forcing on gas concentration. *Journal of Geophysical Research (Atmospheres)*, 119(24):13,683–13,689, Dec. 2014. doi: 10.1002/2014JD022466.

T. Ikeda and E. Tajika. A study of the energy balance climate model with CO_2-dependent outgoing radiation: implication for the glaciation during the Cenozoic. *Geophys. Res. Lett.*, 26:349–352, Feb. 1999. doi: 10.1029/1998GL900298.

Y. Kanzaki and T. Murakami. Estimates of atmospheric CO_2 in the Neoarchean-Paleoproterozoic from paleosols. *Geochimica et Cosmochimica Acta*, 159:190–219, June 2015. doi: 10.1016/j.gca.2015.03.011.

J. F. Kasting. Theoretical Constraints on Oxygen and Carbon Dioxide Concentrations in the Precambrian Atmosphere. *Precambrian Res.*, 34:205–229, 1987. doi: 10.1016/0301-9268(87)90001-5.

H. Kienert, G. Feulner, and V. Petoukhov. Faint young Sun problem more severe due to ice-albedo feedback and higher rotation rate of the early Earth. *Geophys. Res. Lett.*, 39:L23710, Dec. 2012. doi: 10.1029/2012GL054381.

H. Kienert, G. Feulner, and V. Petoukhov. Albedo and heat transport in 3-D model simulations of the early Archean climate. *Clim. Past*, 9:1841–1862, 2013. doi: 10.5194/cp-9-1841-2013.

G. Kopp and J. L. Lean. A new, lower value of total solar irradiance: Evidence and climate significance. *Geophys. Res. Lett.*, 38:L01706, 2011. doi: 10.1029/2010GL045777.

M. Kunze, M. Godolt, U. Langematz, J. L. Grenfell, A. Hamann-Reinus, and H. Rauer. Investigating the Early Earth Faint Young Sun Problem with a General Circulation Model. *Planet. Space Sci.*, 98:77–92, 2014. doi: 10.1016/j.pss.2013.09.011.

G. Le Hir, Y. Teitler, F. Fluteau, Y. Donnadieu, and P. Philippot. The faint young Sun problem revisited with a 3-D climate-carbon model - Part 1. *Clim. Past*, 10:697–713, Apr. 2014. doi: 10.5194/cp-10-697-2014.

O. R. Lehmer, D. C. Catling, R. Buick, D. E. Brownlee, and S. Newport. Atmospheric CO_2 levels from 2.7 billion years ago inferred from micrometeorite oxidation. *Science Advances*, 6(4):eaay4644, Jan. 2020. doi: 10.1126/sciadv.aay4644.

J. P. Lewis, A. J. Weaver, S. T. Johnston, and M. Eby. Neoproterozoic "snowball Earth": Dynamic sea ice over a quiescent ocean. *Paleoceanography*, 18:1092, Dec. 2003. doi: 10.1029/2003PA000926.

J. P. Lewis, A. J. Weaver, and M. Eby. Snowball versus slushball Earth: Dynamic versus nondynamic sea ice? *J. Geophys. Res.*, 112(C11):C11014, Nov. 2007. doi: 10.1029/2006JC004037.

R. S. Lindzen and B. Farrell. Some Realistic Modifications of Simple Climate Models. *J. Atmos. Sci.*, 34:1487–1501, Oct. 1977. doi: 10.1175/1520-0469(1977)034<1487:SRMOSC>2.0.CO;2.

Y. Liu, W. R. Peltier, J. Yang, and G. Vettoretti. The initiation of Neoproterozoic "snowball" climates in CCSM3: the influence of paleocontinental configuration. *Climate of the Past*, 9:2555–2577, Nov. 2013. doi: 10.5194/cp-9-2555-2013.

Y. Liu, W. R. Peltier, J. Yang, G. Vettoretti, and Y. Wang. Strong effects of tropical ice-sheet coverage and thickness on the hard snowball Earth bifurcation point. *Climate Dynamics*, 48(11-12):3459–3474, June 2017. doi: 10.1007/s00382-016-3278-1.

M. Montoya, A. Griesel, A. Levermann, J. Mignot, M. Hofmann, A. Ganopolski, and S. Rahmstorf. The earth system model of intermediate complexity CLIMBER-3α. Part 1: description and performance for present-day conditions. *Climate Dynamics*, 25(2-3):237–263, Aug. 2005. ISSN 0930-7575. doi: 10.1007/s00382-005-0044-1.

G. R. North. Analytical Solution to a Simple Climate Model with Diffusive Heat Transport. *Journal of Atmospheric Sciences*, 32(7):1301–1307, July 1975a. doi: 10.1175/1520-0469(1975)032<1301:ASTASC>2.0.CO;2.

G. R. North. Theory of Energy-Balance Climate Models. *Journal of Atmospheric Sciences*, 32:2033–2043, 1975b. doi: 10.1175/1520-0469(1975)032<2033:TOEBCM>2.0.CO;2.

G. R. North. Multiple solutions in energy balance climate models. *Global and Planetary Change*, 2(3):225–235, Aug. 1990. doi: 10.1016/0921-8181(90)90003-U.

G. R. North and J. Coakley, James A. Differences between Seasonal and Mean Annual Energy Balance Model Calculations of Climate and Climate Sensitivity. *Journal of Atmospheric Sciences*, 36(7):1189–1204, July 1979. doi: 10.1175/1520-0469(1979)036<1189:DBSAMA>2.0.CO;2.

G. R. North, R. F. Cahalan, and J. Coakley, James A. Energy Balance Climate Models. *Reviews of Geophysics and Space Physics*, 19:91, Feb. 1981. doi: 10.1029/RG019i001p00091.

G. R. North, D. A. Short, and J. G. Mengel. Simple energy balance model resolving the seasons and the continents - Application to the astronomical theory of the ice ages. *J. Geophys. Res.*, 88:6576–6586, Aug. 1983. doi: 10.1029/JC088iC11p06576.

E. J. Öpik. On the causes of palaeoclimatic variations and of the ice ages in particular. *Journal of Glaciology*, 2(13):213–218, Apr. 1953. doi: 10.1017/S0022143000025752.

R. C. Pacanowski and S. M. Griffies. The MOM-3 manual. Technical Report 4, NOAA/Geophyical Fluid Dynamics Laboratory, Princeton, NJ, USA, 1999. URL https://mom-ocean.github.io/assets/pdfs/MOM3_manual.pdf.

V. Petoukhov, A. Ganopolski, V. Brovkin, M. Claussen, A. Eliseev, C. Kubatzki, and S. Rahmstorf. CLIMBER-2: a climate system model of intermediate complexity. Part I: model description and performance for present climate. *Climate Dynamics*, 16(1):1–17, Jan. 2000. ISSN 0930-7575. doi: 10.1007/pl00007919.

R. T. Pierrehumbert, D. S. Abbot, A. Voigt, and D. Koll. Climate of the Neoproterozoic. *Annu. Rev. Earth Pl. Sc*, 39:417–460, May 2011. doi: 10.1146/annurev-earth-040809-152447.

C. J. Poulsen, R. L. Jacob, R. T. Pierrehumbert, and T. T. Huynh. Testing paleogeographic controls on a Neoproterozoic snowball Earth. *Geophys. Res. Lett.*, 29(11):1515, June 2002. doi: 10.1029/2001GL014352.

V. Ramanathan and J. Coakley, J. A. Climate Modeling Through Radiative-Convective Models (Paper 8R0533). *Reviews of Geophysics and Space Physics*, 16:465, Nov. 1978. doi: 10.1029/RG016i004p00465.

G. H. Roe and M. B. Baker. Notes on a Catastrophe: A Feedback Analysis of Snowball Earth. *Journal of Climate*, 23(17): 4694–4703, Sept. 2010. doi: 10.1175/2010JCLI3545.1.

V. Romanova, G. Lohmann, and K. Grosfeld. Effect of land albedo, CO_2, orography, and oceanic heat transport on extreme climates. *Climate of the Past*, 2(1):31–42, June 2006. doi: 10.5194/cp-2-31-2006.

B. E. J. Rose and J. Marshall. Ocean Heat Transport, Sea Ice, and Multiple Climate States: Insights from Energy Balance Models. *Journal of Atmospheric Sciences*, 66(9):2828, Jan. 2009. doi: 10.1175/2009JAS3039.1.

M. T. Rosing, D. K. Bird, N. H. Sleep, and C. J. Bjerrum. No climate paradox under the faint early Sun. *Nature*, 464:744–747, Apr. 2010. doi: 10.1038/nature08955.

R. Rye, P. H. Kuo, and H. D. Holland. Atmospheric carbon dioxide concentrations before 2.2 billion years ago. *Nature*, 378: 603–605, Dec. 1995. doi: 10.1038/378603a0.

S. H. Schneider and T. Gal-Chen. Numerical experiments in climate stability. *J. Geophys. Res.*, 78(27):6182–6194, Sept. 1973. doi: 10.1029/JC078i027p06182.

T. Schneider. The General Circulation of the Atmosphere. *Annual Review of Earth and Planetary Sciences*, 34:655–688, May 2006. doi: 10.1146/annurev.earth.34.031405.125144.

W. D. Sellers. A Global Climatic Model Based on the Energy Balance of the Earth-Atmosphere System. *J. Appl. Meteorol.*, 8: 392–400, June 1969. doi: 10.1175/1520-0450(1969)008.

N. D. Sheldon. Precambrian paleosols and atmospheric CO_2 levels. *Precambrian Res.*, 147:148–155, 2006. doi: 10.1016/j. precamres.2006.02.004.

S. Shen and G. North. A simple proof of the slope stability theorem for energy balance climate models. *Canadian Applied Mathematics Quarterly*, 7:203–215, 1999.

J. V. Strauss and N. J. Tosca. Mineralogical constraints on Neoproterozoic pCO2 and marine carbonate chemistry. *Geology*, 48 (6):599–603, June 2020. doi: 10.1130/G47506.1.

H. Tang and Y. Chen. Global glaciations and atmospheric change at ca. 2.3 Ga. *Geoscience Frontiers*, 4(5):583–596, 2013. doi: 10.1016/j.gsf.2013.02.003.

Y. Teitler, G. Le Hir, F. Fluteau, P. Philippot, and Y. Donnadieu. Investigating the Paleoproterozoic glaciations with 3-D climate modeling. *Earth and Planetary Science Letters*, 395:71–80, June 2014. doi: 10.1016/j.epsl.2014.03.044.

A. Voigt and D. S. Abbot. Sea-ice dynamics strongly promote Snowball Earth initiation and destabilize tropical sea-ice margins. *Clim. Past*, 8:2079–2092, Dec. 2012. doi: 10.5194/cp-8-2079-2012.

A. Voigt and J. Marotzke. The transition from the present-day climate to a modern Snowball Earth. *Climate Dynamics*, 35(5): 887–905, Oct. 2010. doi: 10.1007/s00382-009-0633-5.

A. Voigt, D. S. Abbot, R. T. Pierrehumbert, and J. Marotzke. Initiation of a Marinoan Snowball Earth in a state-of-the-art atmosphere-ocean general circulation model. *Climate of the Past*, 7:249–263, Mar. 2011. doi: 10.5194/cp-7-249-2011.

P. von Paris, H. Rauer, J. Lee Grenfell, B. Patzer, P. Hedelt, B. Stracke, T. Trautmann, and F. Schreier. Warming the early earth – CO_2 reconsidered. *Planet. Space Sci.*, 56:1244–1259, July 2008. doi: 10.1016/j.pss.2008.04.008.

E. T. Wolf and O. B. Toon. Hospitable Archean Climates Simulated by a General Circulation Model. *Astrobiology*, 13:656–673, 2013. doi: 10.1089/ast.2012.0936.

J. Yang, W. R. Peltier, and Y. Hu. The Initiation of Modern "Soft Snowball" and "Hard Snowball" Climates in CCSM3. Part I: The Influences of Solar Luminosity, CO_2 Concentration, and the Sea Ice/Snow Albedo Parameterization. *Journal of Climate*, 25:2711–2736, Apr. 2012a. doi: 10.1175/JCLI-D-11-00189.1.

J. Yang, W. R. Peltier, and Y. Hu. The Initiation of Modern "Soft Snowball" and "Hard Snowball" Climates in CCSM3. Part II: Climate Dynamic Feedbacks. *Journal of Climate*, 25(8):2737–2754, Apr. 2012b. doi: 10.1175/JCLI-D-11-00190.1.

J. Yang, W. R. Peltier, and Y. Hu. The initiation of modern soft and hard Snowball Earth climates in CCSM4. *Climate of the Past*, 8(3):907–918, May 2012c. doi: 10.5194/cp-8-907-2012.