Final report for the DKRZ project bb1092

Climate Dynamics of a (Near-)Snowball

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1. General

- Project number: bb1092
- Applicant: Univ.-Prof. Dr. Aiko Voigt
- Institute: Institute of Meteorology and Climate Research - Department Troposphere Research, Karlsruhe Institute of Technology until 12/2020; University of Vienna since 01/2021
- Period: 01.01.2019 – 31.12.2022

Publications based on this project

a) Peer-reviewed articles

Braun, C., J. Hörner, A. Voigt, and P. Joaquim, 2022a: Ice-free tropical waterbelt during Snowball Earth events questioned by uncertain clouds. Nature Geoscience, 15, 489–493, https://doi.org/10.1038/s41561-022-00950-1.

Hörner, J., A. Voigt, and C. Braun, 2022: Snowball Earth initiation and the thermodynamics of sea ice. Journal of Advances in Modeling Earth Systems. https://doi.org/10.1029/2021MS002734.

Braun, C., A. Voigt, C. Hoose, A. M. L. Ekman, and J. G. Pinto, 2022b: Controls on subtropical cloud reflectivity during a waterbelt scenario for the Cryogenian glaciations. Journal of Climate, https://doi.org/10.1175/JCLI-D-22-0241.1.

b) other publications

Master thesis of Johannes Hörner: The Influence of Sea-ice Parameterizations on the Modelling of Snowball Earth Initiation, August 2020, https://www.imk-tro.kit.edu/english/5734_10384.php

PhD thesis of Christoph Braun: Waterbelt scenario for the Cryogenian glaciations questioned by uncertain mixed-phase clouds, June 2022, to be published at KIT library.

Presentation of the project results at conferences

EGU 2020 - Subtropical clouds stabilize near-Snowball Earth states - Braun, Christoph; Voigt, Aiko; Hörner, Johannes; Pinto, Joaquim G. - display

EXO III - Subtropical clouds stabilize near-Snowball Earth states - Braun, Christoph; Voigt, Aiko; Hörner, Johannes ; Pinto, Joaquim G. - online poster

AGU 2020 - Constraining cloud uncertainty in near-snowball waterbelt scenarios at the outer limit of the habitable zone - Braun, Christoph; Voigt, Aiko; Hörner, Johannes; Pinto, Joaquim G. - oral presentation

AGU 2021 - Constraining Neoproterozoic low-level-cloud reflectivity to assess the plausibility of near-Snowball Earth states - Braun, Christoph; Hörner, Johannes; Voigt, Aiko ; Pinto, Joaquim G.; Hoose, Corinna; Ekmann, Annica M. L. – oral presentation
AGU 2021 - Snowball Earth initiation and the thermodynamics of sea ice - Hörner, Johannes ; Voigt, Aiko ; Braun, Christoph - poster

EGU 2022 - Snowball Earth initiation and the thermodynamics of sea ice - Hörner, Johannes ; Voigt, Aiko ; Braun, Christoph – oral presentation

2. Overview of project goals, implementation, and key results

Geological evidence of active tropical glaciers reaching sea level during the Neoproterozoic (1000 – 541 Million years ago), suggesting a global ocean completely covered in ice, was the key observation in the development of the hard Snowball Earth hypothesis [1,2,3,4]. These conditions are hard to reconcile with the survival of complex marine life through Snowball Earth glaciations [5,6,7], which led to the proposal of alternative waterbelt scenarios that allow for a large-scale refugium in the form of a narrow ice-free strip in the tropical ocean [8,9]. Among the proposed waterbelt scenarios, the so-called Jormungand hypothesis is particularly attractive as it proposes an entire life cycle of the glaciations and rests on well-established atmospheric dynamics and physics [8]. According to the Jormungand hypothesis, the waterbelt climate is stabilized by a weakening of the ice-albedo feedback in the subtropical region [8]. In the subtropics, subsidence associated with the Hadley circulation suppresses precipitation and promotes evaporation of high-albedo snow deposited on sea ice [8]. Hence, subtropical sea ice is snow-free and relatively dark [8]. In this project we investigated whether a Jormungand-waterbelt scenario is a viable explanation for the Neoproterozoic glaciations.

Surprisingly, and in contrast to our own expectations, we found that waterbelt states are not a robust feature of idealized aquaplanet setups. Therefore, instead of answering Q1 to Q4, we focused on Q1 throughout the entire project. To do so, we performed two steps.

In a first step we investigated whether Jormungand-waterbelt states are a robust feature of Earth's past climate using idealized aquaplanet simulations from two climate models run with a variety of cloud treatments in combination with an energy balance model. Our simulations show that geologically relevant waterbelt states are not a robust and naturally emerging feature of climate (Figure 1). As part of this step, we also investigated the impact of the applied sea-ice scheme on Snowball Earth initiation. Specifically, we studied the impact of vertical resolution and brine pockets of ice and the impact of limiting ice thickness to 5 m. The internal heat storage of ice is increased by higher vertical resolution and brine pockets, which weakens surface melting and increases global albedo by allowing snow and ice to persist longer into the summer season. The result is a substantially easier Snowball Earth initiation and an increase in the critical CO2 for Snowball initiation by 50%. Limiting ice thickness impedes Snowball initiation as the removal of excess ice leads to an artificial heat source. Yet, the impact is minor and critical CO2 is decreased by 5% only. The results show that while the sea-ice thickness limit plays only a minor role, the internal heat storage of ice represents an important factor for Snowball initiation and needs to be taken into account when modeling Snowball Earth initiation. The work on sea ice thermodynamics was published in the Journal of Advances in Modeling Earth Systems in 2022.

The most surprising and key contribution of this project is that intense shortwave reflectivity by mixed-phase clouds is needed for geologically-relevant waterbelt states, in addition to a low albedo of bare sea ice that was identified by [8] more than 10 years ago. However, the high uncertainty associated with representing mixed-phase clouds in general circulation models prohibited us to assess whether Neoproterozoic shortwave cloud reflectivity was high (Figure 2) and thus whether a waterbelt climate prevailed during the Neoproterozoic period. This work was published in Nature Geoscience in 2022.

The uncertainty associated with representing clouds in general circulation models is generally known to primarily arise from convection parameterizations and aerosol-cloud interactions [10]. Therefore, in a second step, we investigated whether reducing the required model assumptions associated with the treatment of convection in atmospheric models helps us to assess the plausibility of a waterbelt scenario. First, we showed that unresolved sub-grid scale processes generate substantial differences in Neoproterozoic subtropical cloud reflectivity among general circulation models. Second, we conducted a hierarchy of simulations using the ICOsahedral Nonhydrostatic (ICON) modeling framework, ranging from coarse-scale general circulation model simulations to large-eddy simulations that explicitly resolve atmospheric convective-scale motions. Our hierarchy of simulations supports the existence of highly reflective subtropical clouds if we apply moderate ice nucleating particle concentrations. Third, we tested the sensitivity of cloud reflectivity to the abundance of ice nucleating particles. In the presence of high but justifiable ice nucleating particle concentrations, cloud reflectivity is strongly reduced (Figure 3). Hence, the existence of stable waterbelt states does critically depend on the abundance of ice nucleating particles. We concluded that explicitly resolving convection can help to constrain Neoproterozoic cloud reflectivity, but limited knowledge concerning Neoproterozoic aerosol conditions hampers strong constraints.

Overall, given the large uncertainty in mixed-phase clouds and their interaction with radiation, waterbelt states remain an uncertain feature of Earth’s climate. Our results strongly question the idea that waterbelt scenarios can explain the Neoproterozoic geology. Thus, our project suggests that Neoproterozoic life likely faced the harsh conditions of a hard Snowball Earth.

Although we did not address the research questions Q2 to Q4, our results provide a new basis for interpreting past and future modeling studies of Neoproterozoic climate that take into account continents, ocean heat transport and sea-ice dynamics.

Furthermore, the results of this project were featured in two press releases by the Karlsruher Institute of Technology (https://www.kit.edu/kit/pi_2022_053_wolken-spielten-wichtige-rolle-in-der-klimageschichte.php) and the University of Vienna (https://medienportal.univie.ac.at/media/aktuelle-pressemeldungen/detailansicht/artikel/schneeball-erde-wolken-spielten-entscheidende-rolle-in-der-klimageschichte/).

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Figures

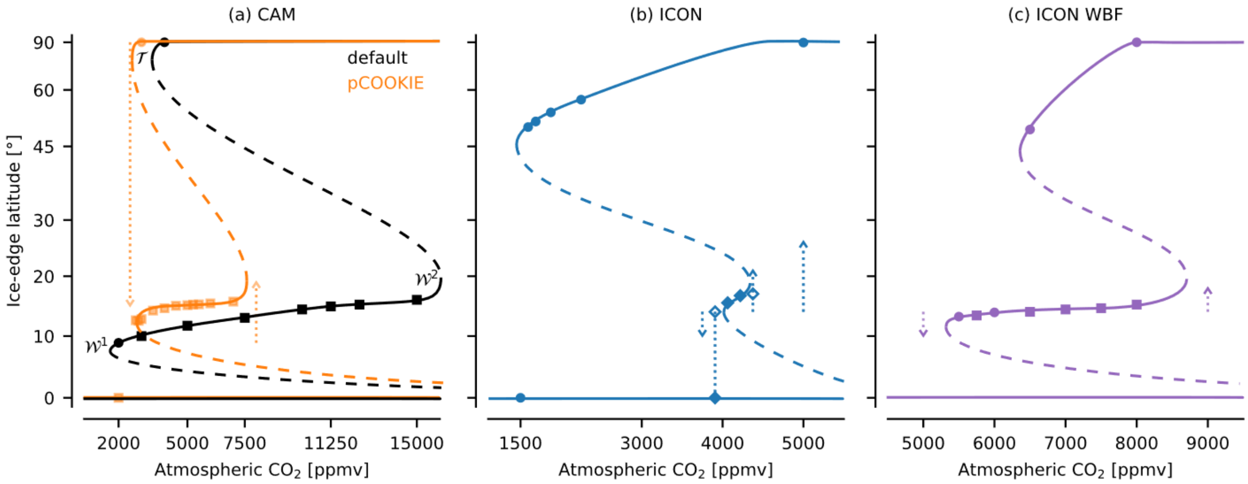

Figure 1: Low-latitude clouds control the existence and absence of waterbelt states in the GCMs CAM and ICON. Bifurcation diagrams of global-mean ice edge versus atmospheric CO2 concentrations for (a) CAM in its default configuration and with clouds made transparent to radiation in a narrow tropical region (pCOOKIE), (b) the default configuration of ICON, and (c) ICON with less efficient Wegener-Bergeron-Findeisen (WBF) process. Filled symbols show stable states. Circles show simulations initialized from ice-free conditions, squares show simulations initialized from stable waterbelt states, and diamonds represent simulations initialized from transient waterbelt states. Unfilled diamonds mark slowly drifting simulations that remain in a waterbelt-like state for at least 40 years, with arrows indicating the drift of the ice edge. Lines are drawn as best guesses of equilibrium states, with solid lines indicating stable and dashed lines indicating unstable states. T , W1, and W2 here label the bifurcation points (nose points). Bifurcation points mark rapid unstable transitions between temperate and waterbelt/Snowball climate (T), waterbelt and Snowball climate (W1), and waterbelt and temperate climate (W2). The waterbelt climate is represented by the solid line located at ice-edge latitudes between 10° and 20°.

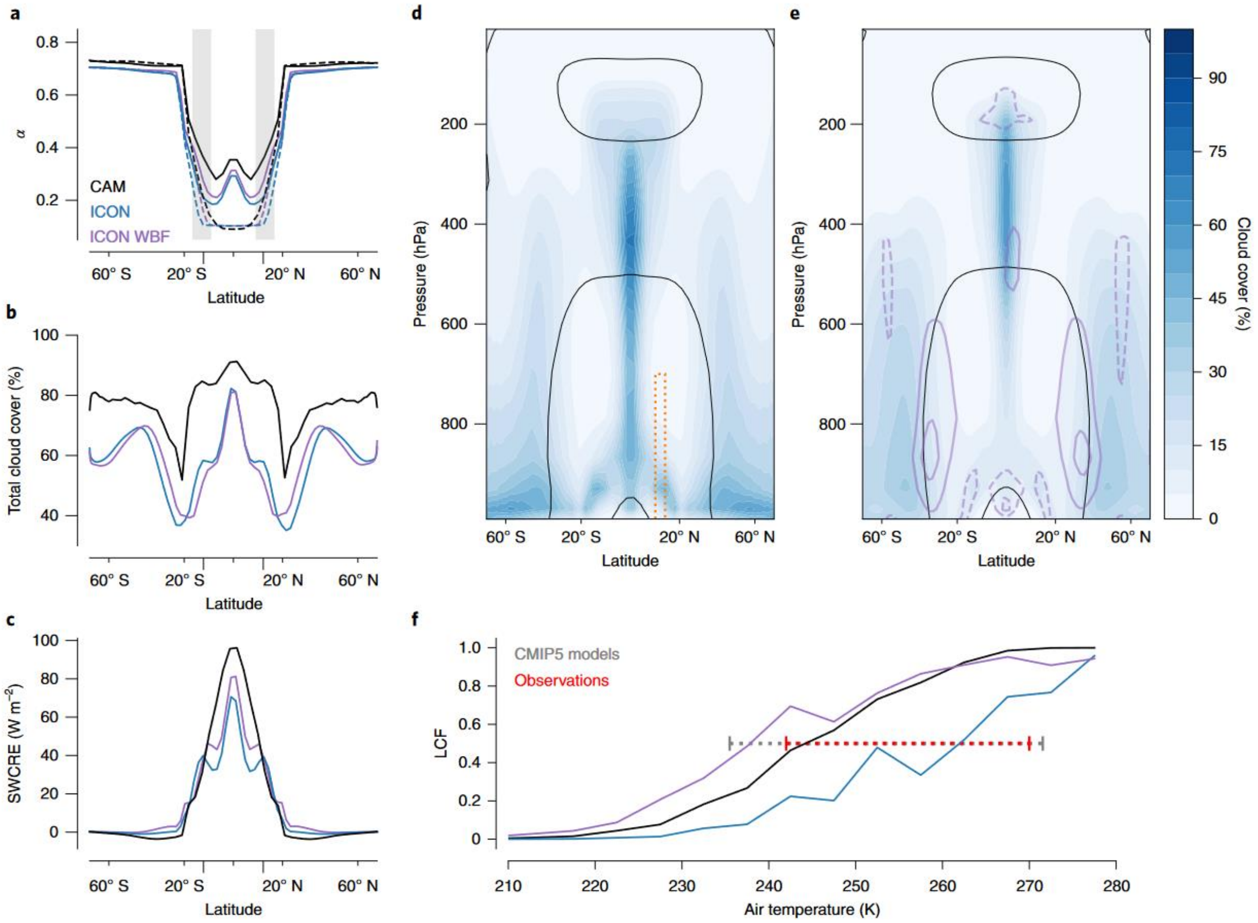

Figure 2: Differences in clouds and their shortwave cloud-radiative effect (SWCRE) as obtained from the general circulation models (GCMs) CAM and ICON as well as ICON with modified Wegener-Bergeron-Findeisen process (ICON WBF). (a) Zonal-mean annual-mean planetary albedo α for all-sky (solid) and clear-sky conditions (dashed), (b) total cloud cover, and (c) SWCRE averaged over all stable waterbelt states for each model. The grey band in (a) indicates the range of global-mean ice-edge latitudes for all stable equilibrium states found in CAM, ICON, and ICON WBF simulations. (d,e) Zonal-mean cloud cover together with 273 K, 235 K, and 192 K isotherms in CAM and ICON for simulations with comparable global-mean ice cover. Orange dotted box in (d) shows region of CAM pCOOKIE modification for Northern hemisphere. Purple contours in (e) show cloud-cover difference between ICON WBF and ICON (contour interval of 3%; positive differences in solid). (f) Liquid condensate fraction (LCF) from simulations shown in (d) and (e). The range of temperatures for which liquid and ice are equally prevalent for 26 Coupled Model Intercomparison Project phase 5 (CMIP5) GCMs is shown in grey. The red line shows the combined observational range of ground-based LIDAR and air craft measurements [11].

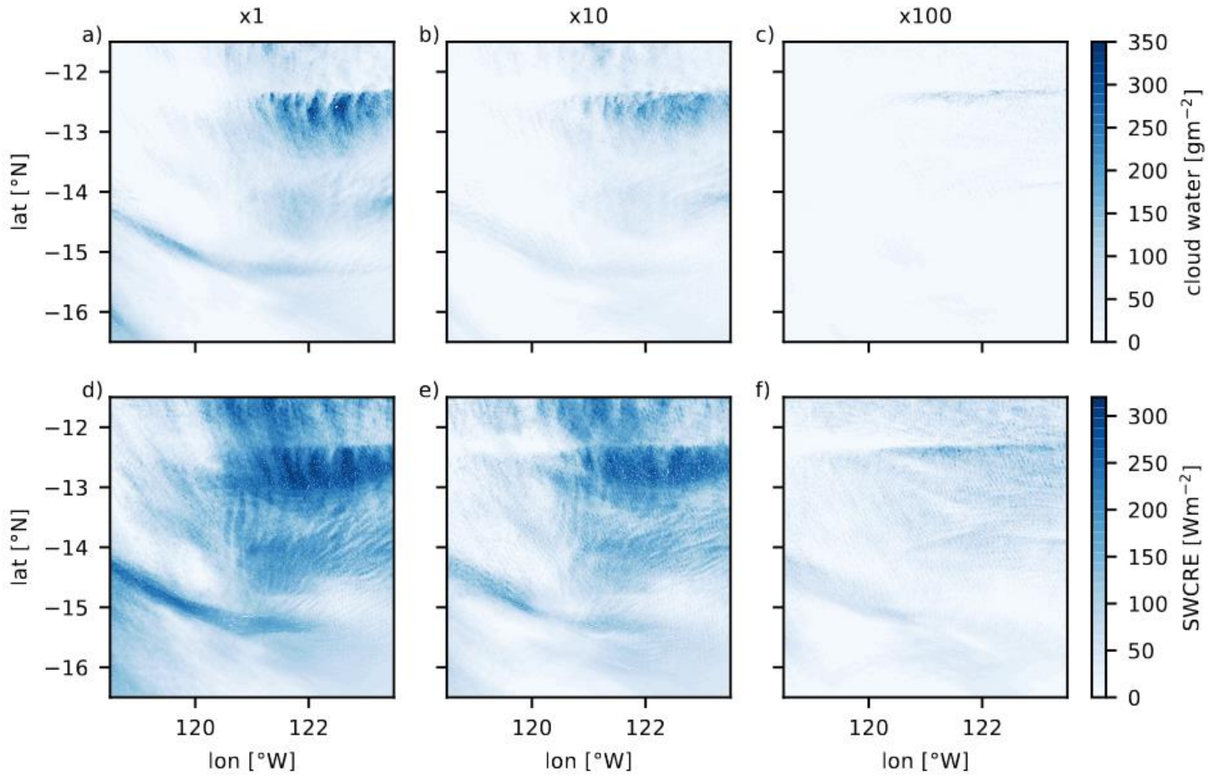

Figure 3: Vertically integrated cloud water a) to c) and shortwave cloud-radiative effect (SWCRE) at top of-the-atmosphere d) to f) over a subtropical ice-edge simulated with ICON in large-eddy mode. x1 (left) denotes the reference concentration of ice nucleating particles (INPs). x10 (middle) and x100 (right) denote INP concentrations that are increased by factors of 10 and 100, respectively.