Project: **1092**
Project title: **Climate Dynamics of a (Near-)Snowball Earth**
Principal investigator: **Aiko Voigt**
Report period: **2020-11-01 to 2021-08-31**

As of 30 July, 2021 we have performed the following simulations:

Simulation	#Simulations	Years/ Simulation	Years	Nh	Work [GB]	Arch [GB]
Model setup ICON-LEM	3	Single days and hours	3 days in total	8074	Total: 54968	2841
ICON-A with modified cloud microphysics	22	10-300 years	~2000 years	26809	-	-

In the first half of 2021 we were unfortunately to a large extent not able to use the granted resources due to personal reasons (including an extended leave of one project member and the move to University of Vienna of two other project members). This leaves us with 45513 nodehours. Archiving will take place in fall 2021.

We continued our study of the climate dynamics of pan-glaciated Snowball Earth states, focusing on the impact of mixed-phase clouds on the existence of low-latitude waterbelt states based on the so-called Jormungand mechanism. The Jormungand mechanism relies on the large albedo contrast between bright snow-covered sea ice and relatively dark snow-free sea ice. In the aquaplanet simulations of Abbot et al. (2011), this allowed for a stable equilibrium state with a sea-ice latitude very close to the equator (near 10° latitude).

To test the robustness of our hypothesis that highly reflective mixed-phase clouds, i.e. mixed-phase clouds with a high liquid condensate fraction (LCF), are required to sustain a stable waterbelt climate, we set up additional ICON-A simulations. We weakened the liquid-to-ice conversion in mixed-phased clouds via the parameterized Bergeron-Findeisen process in ICON-A as suggested in Mauritsen and Roeckner (2020), in order to achieve cloud properties that are more similar to the cloud properties simulated in CAM3 by Abbot et al. (2011). Weakening the liquid-to-ice conversion strongly increases LCF and moderately increases planetary albedo α in ICON-A (Fig. 1).

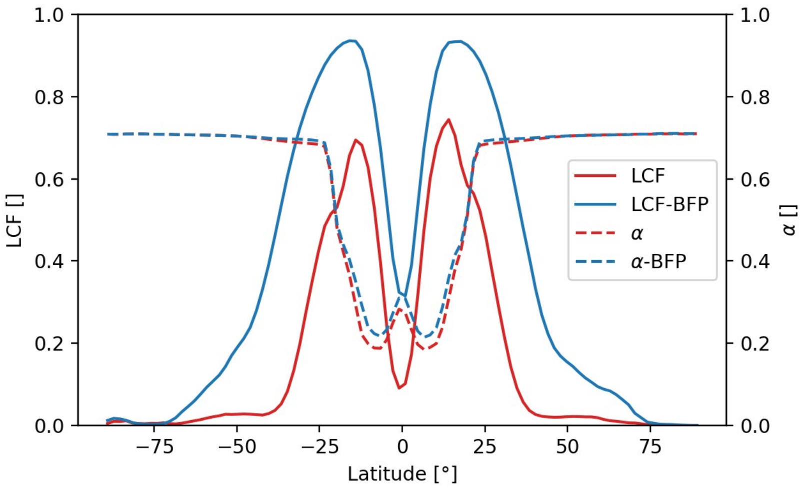

Figure 1: Liquid condensate fraction (solid lines) and planetary albedo (dashed lines) with weakened liquid-to-ice conversion (blue) and default (red) in ICON-A. Simulations were initialized with a CO2 content of 4219ppmv and an sea-ice edge at 14°, results are averaged over one year.

Preliminary results show that the moderate increase in planetary albedo in fact is sufficient to stabilize the waterbelt climate in ICON-A (Fig. 2). Moreover, the simulated waterbelt states are accessible from a warmer climate regime and therefore provide a basis to consider waterbelt scenario as a geologically relevant alternative to the classical Snowball Earth hypothesis. Right now, we are performing simulations to reproduce bifurcation diagrams mapped with different configurations of ICON-A and CAM3. Concerning future studies, these results enable us to use ICON-A in further extensive analyses of waterbelt climates in a more realistic setup (e.g. by considering continents and ocean and sea ice dynamics).

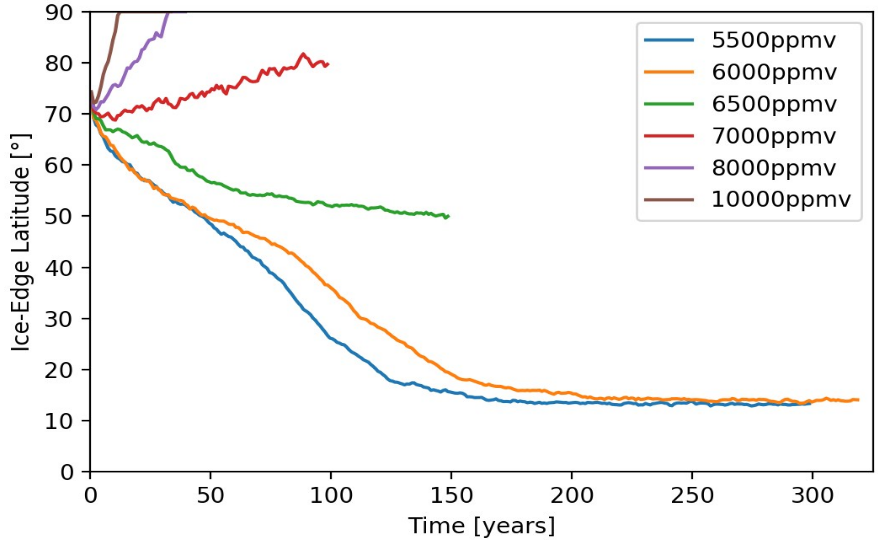

Figure 2: Latitude of the sea-ice edge dependent on time for ICON-A simulations with weakened liquid-to-ice conversion, initialized with an ice-free aquaplanet and different atmospheric CO2 contents. The simulations with 5500ppmv and 6000ppmv CO2 result in a stable sea-ice edge at ~14°, indicating a waterbelt state that is accessible from ice-free conditions.

Yet, one open question is which magnitude of planetary albedo arising from clouds can be expected under Neoproterozoic conditions. Since mixed-phase clouds are subject to major uncertainties in global climate models (e.g., McCoy2015), we initiated a study to constrain simulated mixed-phase clouds in a near-Snowball-Earth climate by high-resolution simulations. The study is designed in three steps:

1) Inter-model comparison at global scale between ICON-A, ICON-NWP and CAM3
2) Intra-model comparison across resolutions within ICON-NWP (incld. LAM) and ICON-LEM
3) Intra-model comparison across atmospheric mineral dust aerosol loading

Step 1) has already been completed and contains a comparison of the near-Snowball subtropical atmospheric circulation simulated in ICON-A, CAM3 and ICON-NWP at a horizontal resolution of around 160 km. The major results are: ICON-NWP largely supports the high cloud reflectivity simulated in CAM3 on a global scale. Cloud reflectivity in the subtropical region arises from stratocumulus cloud decks trapped below the descending branch of the Hadley cell (as in the present-day climate) but also from frequent convective events, that arise from baroclinic waves triggered by strong meridional temperature gradients. The latter is a robust feature among all three models, but plays a minor role concerning overall cloud reflectivity. Because these strong convective events seem to robustly trigger thick cloud decks across models, there is only minor differences arising from convective areas across the three models. Therefore, we find the strongest differences in cloud reflectivity between models in regions of subsidence.

We therefore focus the simulations conducted as part of step 2) on regions of subsidence with low-level stratocumulus cloud decks. A lot of work has been devoted to choosing appropriate and representative subdomains and robustly setting up the ICON-LAM and ICON-LEM simulations. Preliminary results from ICON-LAM simulations seem to confirm the high subtropical cloud reflectivity found in ICON-NWP on a global scale. ICON-LEM simulations are close to production runs.

In step 3) we will finally vary the atmospheric content of mineral dust, which acts as ice nucleation particle, thus impacting the microphysical processes of mixed-phase clouds. Mineral dust is expected to be the major aerosol species present in a near-Snowball climate.

Project publications

A manuscript describing the results obtained in the first part of this project is currently prepared for revision. An oral presentation of preliminary results of the high-resolution simulations took place at AGU2020. Results of ICON-LEM simulations will be submitted as part of an abstract for AGU2021. A publication of the results of our investigation of the impact of sea-ice schemes on Snowball Earth initiation was submitted to JAMES in July 2021.

References

Abbot, D. S., A. Voigt, and D. Koll, 2011: The Jormungand Global Climate State and Implications for Neoproterozoic Glaciations, Journal of Geophysical Research-Atmospheres, 116, D18103.

McCoy, D. T.; Hartmann, D. L.; Zelinka, M. D.; Ceppi, P. & Grosvenor, D. P., 2015: Mixed-phase cloud physics and Southern Ocean cloud feedback in climate models, *Journal of Geophysical Research: Atmospheres, 120*, 9539-9554.