Project: **1092**

Project title: **Climate Dynamics of a (Near-)Snowball Earth**

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Report period: **2019-01-01 to 2019-12-31**

By the 28th of October 2019 we have performed the following simulations:

| Simulation | # Simulations | Years/Simulation | Years | Nh | Work [GB] | Arch [GB] |
|---|---|---|---|---|---|---|
| Model setup | 1 | 700 | 700 | 12,600 | 500 | 0 |
| Mapping CO2-ice diagrams ICON-A | 15 | 150 | 2,250 | 40,500 | 10,000 | 10,000 |
| Mapping CO2-ice diagrams CAM3 | 50 | 150 | 7,500 | 3,750 | 8,000 | 8,000 |

This leaves us 20,000 Nh for the remainder of this year. These will be used for completing the mapping of diagrams and first simulations to study the impact of the sea ice scheme on our simulation setup. Archiving of our data is scheduled for late November of this year.

So far, we studied the climate dynamics of pan-glaciated Snowball Earth states, focusing on factors that stabilize or destabilize low-latitude ice edges and influence the Jormungand hysteresis. The Jormungand hypothesis rests 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). The corresponding $CO_2$ vs- sea-ice latitude bifurcation diagram is shown in Fig. 1 (left).

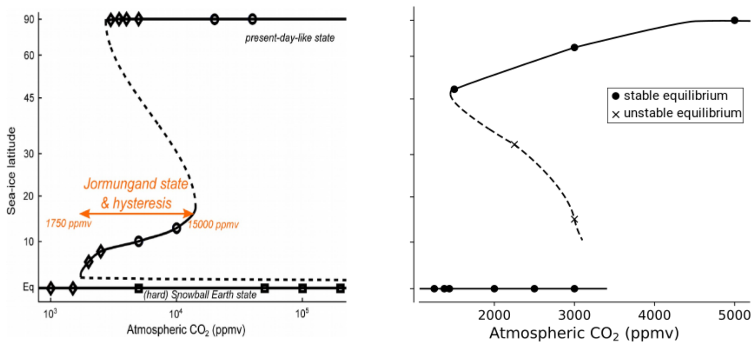


*Fig. 1: $CO_2$ vs. sea-ice latitude bifurcation diagram of the CAM3 global atmosphere model coupled to a slab ocean in idealized aquaplanet setup with zero ocean heat transport. The Jormungand state exists over a wide range of $CO_2$ values from 1,750-15,000 ppmv and is separated from the stable (hard) Snowball Earth state and a present-day-like state by bifurcations and unstable solutions (dashed lines) (left). Bifurcation diagram of the ICON-A global atmosphere model in the same setup as CAM3. No stable Jormungand state has been found. Stable equilibrium states (dots) exist only with high-latitude sea ice edges or as Snowball states. Crosses mark approximately determined positions of unstable equilibrium states (right).*

As a first step of our long-term goal – demonstrating the existence of significant Jormungand hysteresis in a global coupled climate model -  we studied whether the Jormungand hypothesis is a robust feature of idealized aquaplanet setups. Abbot et al. (2011) demonstrated Jormungand hysteresis in the CAM3 and ECHAM5 atmosphere general circulation models in an idealized aquaplanet setup, using a thermodynamic mixed layer ocean and a thermodynamic sea ice scheme.

To repeat the aquaplanet simulations of Abbot et al. (2011) with the ICON-A atmosphere model, we implemented a thermodynamic mixed layer ocean and a thermodynamic sea ice scheme (Semtner 0-layer model) in ICON-AES 1.3.00 (unmodified version described in Giorgetta et al. (2018)). The bifurcation diagram resulting from our ICON-A simulations is shown in Fig. 1 (right). As indicated, we found equilibrium states either with high-latitude sea ice edges or with an entirely ice covered ocean. However, we did not find a stable Jormungand state. We can not exclude that a stable Jormungand state may exist within $CO_2$ concentrations between 3000 ppmv and 5000 ppmv. Nevertheless, the Jormungand state would not be directly accessible by cooling from a warmer climate (hidden Jormungand state) and the corresponding hysteresis would be too narrow for geological significance. We also found two unstable equilibria at 2250 ppmv and 3000 ppmv. Their position was approximated to be in between two slightly differing transient states that are slowly drifting towards a Snowball and an ice-free state, respectively. The two transient states at 3000 ppmv remain in a Jormungand-like state with a sea ice edge around 15° latitude for about 100 years before transitioning to a colder or warmer state. This enabled us to compare the unstable Jormungand-like state in ICON-A with the stable Jormungand state found in CAM3. A significant difference is the considerably lower annual mean planetary albedo in the tropics and subtropics in ICON-A (~0.25) compared to CAM3 (~0.35). The difference in planetary albedo can be related to a stronger top-of-the-atmosphere shortwave cloud-radiative effect in CAM3 compared to ICON-A and proves to be substantial for the stability of the Jormungand state as inferred from a one-dimensional energy balance model proposed by Abbot et al (2011).

Based on these results the robustness of the Jormungand hypothesis in idealized aquaplanet setups may be questioned. Since we found that the main difference between ICON-A and CAM3 simulations manifests in clouds, we hypothesized that the existence of significant Jormungand hysteresis in atmosphere models strongly depends on the representation of clouds in general circulation models.

To test this hypothesis we modified the representation of clouds in CAM3 in two ways: First, we globally made clouds transparent to solar and thermal radiation as in the Clouds On-Off Klimate Intercomparison Experiment (COOKIE) defined by Stevens et al. (2012). Second, we performed a partial COOKIE (pCOOKIE) with clouds transparent to radiation in vertical columns in the subtropics between 17° and 23° latitude. The corresponding bifurcation diagrams are shown in Fig. 2. Due to the overall cooling effect of clouds on the atmosphere, the bifurcation diagram for COOKIE is shifted to much lower $CO_2$ concentrations. However, it is evident that the structure of the bifurcation diagram is also significantly impacted by the removal of clouds. The impact on atmospheric radiative fluxes for pCOOKIE is more subtle and therefore allows for a direct comparison of the hysteresis of the Jormungand state. We found a hidden Jormungand state and a significantly decreased hysteresis with a maximum range of $CO_2$ concentrations between 2500 ppmv to 7000 ppmv, compared to Abbot et al. (2011) with 1750 ppmv to 15000 ppmv.

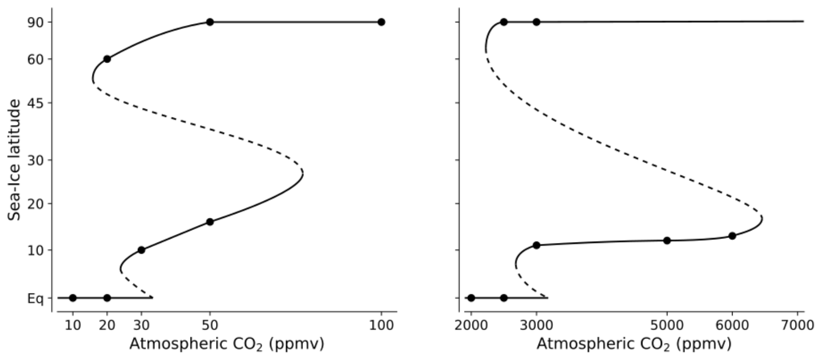


*Fig. 2: Bifurcation diagram of the CAM3 global atmosphere model with clouds transparent to radiation globally (left) and within vertical columns in the subtropics between 17° and 23° latitude only (right). Note the modified structure of the bifurcation diagrams and the decreased hysteresis compared with Fig. 1 (left).*

We are currently debating further implications of these results and plan to assess, whether a modification of clouds can not only destabilize Jormungand state in CAM3 but can also stabilize the Jormungand state in ICON-A. Furthermore, we aim to compare the spread in the response of climate models caused by the representation of clouds with the spread caused by other components of our idealized model setup. To this end, we plan to conduct ICON-A simulations with a more elaborate sea ice scheme, e.g. a Semtner 3-layer model, since ice vertical resolution has been reported as a relevant impact in cold climate states by Abbot et al. (2010).

**References**

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