Climate-modelling studies of the faint young Sun problem and of the relation between the AMOC and a regional sea-level gradient

Hendrik Kienert

Understanding the origin and different phases of the development of the Earth has long been a motivation for fundamental research in the geosciences. The climate of the Archean Eon (3.8 – 2.5 billion years ago), the time period in which life emerged, is especially puzzling: In a world very different from today, when the planet was spinning faster about its own axis and had a much smaller continental fraction in its early stages, the Sun was up to 25% less luminous - however, there is strong evidence for liquid surface waters.

Solutions to this `faint young Sun problem' almost certainly demand higher greenhouse-gas concentrations. While geochemical estimates for the composition of the early atmosphere are arising, computer simulations are needed to assess which exact conditions could have been sufficient to prevent the Earth from falling into a `snowball state'. As previous research mainly relied on one-dimensional and highly simplified models which did not capture several important effects such as the ice-albedo feedback, we have modified a three-dimensional fully coupled ocean-atmosphere-sea-ice model in order to adequately represent those Archean boundary conditions which are well known and to vary others in an ensemble of simulations according to their uncertainty range. Such adjustments were for example necessary for the topography, the rotation rate of the Earth and the radiative-transfer scheme for high CO_2 partial pressures.

Using this modified version of the model in a large set of simulations, we found that significantly higher greenhouse-gas concentrations than previously thought are needed to explain why the ocean surface was not fully frozen. For the middle and late Archean, our results indicate that so far preferred CO_2/CH_4 greenhouse solutions could be in conflict with geochemical data.

In addition to quantifying the impact of carbon dioxide on sea-ice fraction and temperature, more extensive analyses of potential early Archean climate states were performed in order to better understand the processes governing the energy balance of the early Earth. We have found a reduction in meridional heat transport compared to today with contributions from the ocean as well as the atmosphere and a resulting overall steeper latitudinal temperature profile. Ocean surface currents are largely zonal; and the meridional overturning cells, which turn out to mirror the Hadley and Ferrel cells with respect to their latitudinal extent, are shallow.

There are significant uncertainties with respect to the topography and the radiative transfer in CO_2-rich atmospheres, and their impact has been investigated in a sensitivity study. Furthermore, a special focus has been put on analyzing the effect of the higher rotation rate on the climate system. The consequences for the critical CO_2 partial pressure following from the uncertainty involved in determining the early Earth's rotation rate are not negligible. However, it turns out that this does not change our results qualitatively. Finally, we provide the relation between global mean temperature and surface albedo from our simulations as a parameterization of the ice-albedo effect to be used in one-dimensional models.

Studying the climate of the distant past with the large uncertainties involved requires a model which is sufficiently fast to allow for a very large number of equilibrium simulations but which at the same time provides a good representation of the different relevant climate interactions. In this respect, our model constitutes an appropriate compromise and is thus also well-suited for idealized ensemble simulations aiming at a better principal understanding of the present and future climate. Making use of this strength of our model, it was applied in an additional part of this thesis to a study of the relation between present-day ocean circulation and sea level in the Atlantic.

The Atlantic meridional overturning circulation (AMOC) plays a crucial role in setting up relatively warm temperatures in the North Atlantic region. Its strength is known to be sensitive to different changes in the climate system, with a weakening or a potential shut-down having severe consequences. As direct monitoring of the AMOC is difficult, indirect measurements via satellite altimetry of the sea surface have been suggested. A simple linear relation between a broad sea-level gradient and the AMOC strength is motivated by theoretical considerations and the results of earlier studies. In a large set of model simulations, we tested if such a relation holds for three different idealized forcing mechanisms (freshwater input to the convection sites, decrease of Southern Ocean winds, increase of CO_2 concentration) as well as for more realistic climate scenarios of the 21st century. Our results show that while there appears to be a linear relation in case of the first two forcing types, it does not hold under greenhouse warming and the more realistic projections, which excludes this approach as an AMOC diagnostic.