International Max Planck Research School on Earth System Modelling

Snowball Earth – Initiation and Hadley Cell Dynamics

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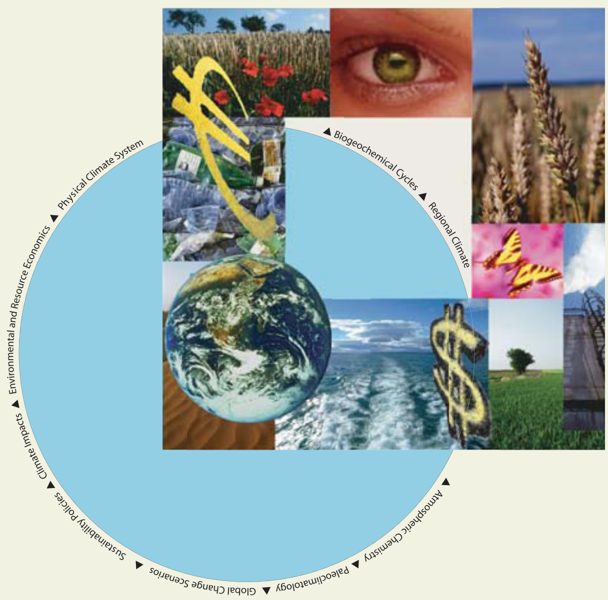

Abstract

I use climate model simulations to investigate the initiation of a Snowball Earth for present-day as well as Marinoan ($\sim$ 635 million years before present) surface boundary conditions, and to study the dynamics of the Hadley cell in a Snowball Earth atmosphere.

Using the coupled atmosphere-ocean general circulation model ECHAM5/MPI-OM in a present-day setup, I find that the modern Snowball Earth bifurcation point is between 91 and 94% of the present-day total solar irradiance (TSI) when atmospheric carbon dioxide is set to its pre-industrial level. The Snowball Earth bifurcation point as well as the transition times are well reproduced by a zero-dimensional energy balance model of the global-mean ocean potential temperature. During the transition, the asymmetric distribution of continents between the Northern and Southern Hemispheres causes heat transports toward the more water-covered Southern Hemisphere. Moreover, stable states can have no greater than 56.6% sea-ice cover.

Using the same model in a Marinoan setup, I show that changing the surface boundary conditions from present-day to Marinoan, which includes a shift of continents to low latitudes, induces a global mean cooling of 4.6 K. The Marinoan Snowball Earth bifurcation point for pre-industrial carbon dioxide is between 95.5 and 96% of the present-day total TSI, illustrating that low-latitude continents facilitate Snowball Earth initiation. A Snowball Earth for TSI reduced to 94% of its present-day value is prevented by quadrupling atmospheric carbon dioxide with respect to its pre-industrial level. The zero-dimensional energy balance model of global-mean ocean potential temperature again successfully predicts the Snowball Earth bifurcation point. States with sea-ice cover above 55% are unstable, akin to what I find for the present-day setup. This shows that ECHAM5/MPI-OM does not exhibit stable states with near-complete sea-ice cover but open equatorial waters. In summary, my results rebut previous conclusions that Snowball Earth initiation would require "extreme" forcings.

Using the atmosphere general circulation model ECHAM5, I investigate the tropical meridional circulation of a Snowball Earth atmosphere. I find that the dynamics of the Snowball Earth Hadley cell differ substantially from the dynamics of the present-day Hadley cell. In the upper branch of the Snowball Earth Hadley cell, mean meridional advection of mean absolute vorticity is not only balanced by eddy momentum flux divergence but also by vertical diffusion. Vertical diffusion also contributes to the meridional momentum balance as it decelerates the Hadley cell by downgradient momentum mixing between its upper and lower branches. I conclude that neither axisymmetric Hadley cell models based on angular momentum conservation nor eddy-permitting Hadley cell models that neglect vertical diffusion of momentum are applicable to a Snowball Earth

atmosphere since both assume an inviscid upper Hadley cell branch. Because vertical diffusion is important for the Hadley cell of a virtually dry Snowball Earth atmosphere, dry atmospheres in general should not be considered as a-priori simpler testcases for Hadley cell theories than moist atmospheres.