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Hadley cell dynamics of a cold and virtually dry Snowball Earth atmosphere

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We use the full-physics atmospheric general circulation model ECHAM5 to investigate a cold and virtually dry Snowball Earth atmosphere that results from specifying sea ice as the surface boundary condition everywhere, corresponding to a frozen aquaplanet, while keeping total solar irradiance at its present-day value of 1365 Wm^{-2}. The aim of this study is the investigation of the zonal-mean circulation of a Snowball Earth atmosphere, which, due to missing moisture, might constitute an ideal though yet unexplored testbed for theories of atmospheric dynamics. To ease comparison with theories, incoming solar insolation follows permanent equinox conditions with disabled diurnal cycle.

The meridional circulation consists of a thermally direct cell extending from the equator to 45 N/S with ascent in the equatorial region, and a weak thermally indirect cell with descent between 45 and 65 N/S and ascent in the polar region. The former cell corresponds to the present-day Earth's Hadley cell, while the latter can be viewed as an eddy-driven Ferrell cell; the present-day Earth's direct polar cell is missing. The Hadley cell itself is subdivided into a vigorous cell confined to the troposphere and a weak deep cell reaching well into the stratosphere.

The dynamics of the vigorous Snowball Earth Hadley cell differ substantially from the dynamics of the present-day Hadley cell. The zonal momentum balance shows that in the poleward branch of the vigorous Hadley cell, mean flow meridional advection of absolute vorticity is not only balanced by eddy momentum flux convergence but also by vertical diffusion. Inside the poleward branch, eddies are more important in the upper part and vertical diffusion is more important in the lower part. Vertical diffusion also contributes to the meridional momentum balance as it decelerates the vigorous Hadley cell by downgradient momentum mixing between its poleward and equatorward branch. Zonal winds, therefore, are not in thermal wind balance in the vigorous Hadley cell.

Suppressing vertical momentum diffusion above 870 hPa results in a doubling of the vigorous Hadley cell strength. Simulations where we only suppress either vertical diffusion of zonal or meridional momentum show that this doubling can be understood from the decelerating effect of vertical diffusion in the meridional momentum balance. Comparing our simulations with theories, we conclude that neither the axisymmetric Hadley cell model of Held & Hou (1980) nor the eddy-permitting model of T. Schneider et al. (2005, 2006, 2008) are applicable to a Snowball Earth atmosphere since both assume an inviscid upper Hadley cell branch.