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Nonlinear dynamics of the Hadley cell in shallow water models

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The steady state nonlinear dynamics of the Hadley circulation is studied using a hydrostatic shallow water model in the equatorial beta-plane where the frictional losses are parameterized with Rayleigh friction coefficients. The fully nonlinear solution is produced for a single-layer model, for a two-layer model with a lid, for a two-layers model with a free surface, and for a three active layers with a lid.

Results for the solstitial and for the equinoctial position of the forcing diabatic source are presented. In the limit case of a frictionless balanced flow, the Hadley cells are absent, and the latitudinal width and the intensity of the circulation in the tropics is always specular symmetric about the equator, even when the sun is in the solstitial position, this is because the dynamical response depends on the intensity of the heat source, but not on its shape. The frictionless problem has an explicit analytical solution, whereas, in the presence of friction, the solutions can be constructed with a limited use of numerics.

The validity of the solution with a lid and of the solution in the weak temperature gradient approximation (WTG) in the presence of friction is discussed in relation to the thermal relaxation time and to the width and the depth of the forcing. The rigid lid solution overestimates the geopotential at low values of the friction coefficient, and it underestimate the geopotential at high values of this coefficient, this behavior is enhanced by small frictional losses in the upper layer. The WTG solution always underestimates the latitudinal width of subtropical regions. When the source is off the equator and the source is narrow and intense, as in the case of the West African monsoon, the northwards displacement of the Hadley circulation is large.