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Nonlinear thermally forced circulations in three dimensions

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Large-scale tropical circulations associated with deep moist convection on Earth are not axisymmetric but are instead organized in longitudinally localized patterns consisting of (i) off-equatorial rotational circulations (Rossby gyres), (ii) cross-equatorial divergent flow (local Hadley circulations) and (iii) zonally overturning circulations in the equatorial plane east of the convective heating (forced Kelvin waves). The rotational circulations are deep, extending from mid-troposphere to lower stratosphere, while the horizontal branches of Hadley circulation are shallow, with inflow and outflow layers confined to the lower and upper troposphere, respectively. Both types of circulation are nonlinear in the sense that parcel displacements attributable to these motions are finite (covering a wide latitudinal range) and conservable properties of the flow such as angular momentum and potential vorticity also are advected over a wide range. Anticyclonic gyres in the UT/LS form closed circulations analogous to the "cat's eye" of a stationary Rossby wave critical-layer of finite width straddling the zero wind line. In such places where, in addition, the horizontal divergence is relatively weak, parcel motions are helical with slow ascent or descent in one hemisphere, and air is isolated for a considerable period of time. The situation is quite different in the Hadley outflow layer where (at solstices) interhemispheric exchange is significant and low or anomalous values of potential vorticity are transported a considerable distance into the subtropics or midlatitudes. There is a suggestion that the Hadley outflow is inertially unstable as seen in the formation of shallow velocity layers and narrowing (in the vertical) of the principal outflow layer. Care must be taken interpreting such observations because, in certain regions, a complex meridional velocity profile results from the superposition of opposing rotational and divergent circulations. Inertial instability is one of several possible manifestations of nonlinearity in the large-scale tropical circulation. Others include the shedding of barotropic vortices from UT/LS

anticyclones, the well-known baroclinic instability of subtropical jetstreams, and nonlinear advection of conservable quantities by the large-scale circulation itself. In view of the finite-amplitude (and usually transient) nature of these processes the question arises whether a statistically steady response to tropical heating can be defined taking into account the relevant nonlinearities and unsteadiness. Two general requirements are (i) the flow is nonlinear, with finite displacement of parcels and isopleths of conservable dynamical quantities, and (ii) mechanical forces arising from instabilities of the system further modify the nonlinear solution. Two pathways to a theoretical solution exist. One requires an extension of the axisymmetric nearly inviscid (Schneider-Held-Hou-Lindzen-Plumb) model to three dimensions including longitude; the other, an extension of the Matsuno-Gill model to the nonlinear regime, with parameterized (non-frictional) mechanical forces added to both. In this talk the formulation of the problem is discussed together with a solution method, and the role of conservable properties is highlighted. The distribution of mechanical forces is shown to depend on each of the three components of forced circulation and especially the Kelvin-wave component which is responsible for the formation of a westerly waveguide in the upper troposphere and a preferred locus of Rossby wavebreaking.