Baroclinic instability in an initially stratified differentially heated rotating flow

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The differentially heated rotating annulus is a widely studied experimental apparatus for modeling some large-scale features of the mid-latitude atmosphere (planetary waves, cyclogenesis, etc.) [1]. In the classic set-up, a rotating cylindrical tank is divided into three coaxial sections: the innermost domain is kept at a lower temperature (by a cooling thermostat), whereas the outer rim of the tank is heated. The working fluid in the middle annular gap thus experiences a horizontal radial temperature gradient, which initiates a “sideways-convective” overturning circulation. This arrangement imitates the meridional temperature gradient of the terrestrial atmosphere. The Coriolis effect that arises due to the rotation of the tank can modify this azimuthally symmetric basic flow markedly, and can lead to baroclinic instability, and the formation of cyclonic and anticyclonic eddies in the full water depth. Note, that in the classic set-up the buoyancy-driven circulation is solely maintained by the temperature difference, no other factors affect the density profiles of the working fluid.

In the present work, we study the flow patterns in a modified version of this experiment, in which—besides the aforementioned radial temperature difference—vertical salinity stratification is also present. In such a system, even before rotation is turned on, double diffusive convection sets in within working fluid with a strongly non-homogeneous pattern consisting of a double diffusive staircase at the bottom of the container in the very dense water layers and a shallow convective cell in the top surface layer. In this case, no convective motions are observed at intermediate altitude. The thickness *d* of a given double convective cell is determined by the radial temperature difference and the local vertical salinity gradient. Since radial motions take place due to the presence of these convective cells, the action of the Coriolis force generates strong zonal flows as soon as rotation is started. Both non-dimensional parameters (namely, the Taylor and themal Rossby numbers) which characterize whether the flow is baroclinically stable (zonal flow) or unstable (wave flow) scale with d/Ω^2, Ω being the rotation rate. Thus, the cell thickness *d* (and, therefore, the local vertical density gradient) sets the baroclinic stability of a given double-convective cell. This implies that if one prepares the initial salinity profile properly, it is possible to confine baroclinic instability to certain shallow layers at arbitrary water depths, while the rest of the fluid stays stable. In the baroclinic unstable layers, rings of self-sustaining pancake vortices [2] are generated.

Using the baroclinic wave tank of the Brandenburg University of Technology (Cottbus-Senftenberg, Germany), we obtained infrared thermographic images to measure the temperature distributions at the water surface, and two-dimensional horizontal PIV velocity maps to detect the vortices in the bulk. Based on the PIV data, we introduced statistical measures to quantify the “baroclinicity” of a horizontal slice at a given depth, and analyzed the connections between these “baroclinicity profiles” and the vertical salinity distributions.

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References

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