AN EXPERIMENTAL STUDY OF BAROCLINIC WAVE TRANSITIONS IN A DIFFERENTIALLY HEATED ROTATING ANNULUS WITH SLOPING BOTTOM TOPOGRAPHY

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Abstract A series of laboratory experiments has been carried out in a thermally driven rotating annulus to observe the transition phenomena between the different (axially symmetric, regular and turbulent) flow regimes and the onset of baroclinic instability. The boundaries of the regimes have been systematically mapped and their positions have been expressed in a two-dimensional phase space described by appropriate non-dimensional temperature and rotation rate parameters. A significant shift of these regime boundaries has been observed once a sloping bottom end wall was added to the setup. A transient wave flow regime has also been clearly identified between the axially symmetric and the stable wave flow phases both in the case of flat and sloping bottom topographies. The results have been compared to recent numerical studies [1].

Based on the principle of hydrodynamical similarity, Earth's various large-scale atmospheric flow phenomena can be modelled in surprisingly simple tabletop-size experimental setups. Under laboratory conditions it is possible to control the governing physical parameters and thus to separate different processes that cannot be studied independently in such a complex system as the real atmosphere. Therefore, experiments provide a remarkable test bed to validate and tune numerical techniques and models for meteorological or even climatological prediction. This is also the scope of the Large Scale Dynamics/Models project within the German *MetStröm* initiative, for which the fluid dynamics laboratory of the Brandenburg University of Technology (BTU) provides the "reference experiments" to be described below (see e.g.: [2]).
The classic apparatus to demonstrate the basic large-scale dynamics of the mid-latitude atmosphere is the differentially heated rotating annulus, that has been introduced by D. Fultz in the late 1940s [3]. The setup, as depicted in Fig. 1, consists of three concentric cylinders placed on a turntable. The central compartment is cooled, while the outermost one is heated, thus the working fluid (usually water) in the middle section experiences a radial temperature gradient. These boundary conditions mimic the meridional pattern associated with the differential incoming solar heat flux in the real atmosphere. The characteristic hydrodynamical timescale is determined by the temperature difference ΔT between the outermost and innermost compartments, and without rotation the velocity field would be axially symmetric. (Note, that in such a "sideways convection" configuration there is no minimum ΔT, i.e. *any* finite temperature difference would initiate an overturning flow.) However – since rotation is present – Coriolis' force also acts on the flow, with a magnitude proportional to the flow velocity and the rotation rate Ω.

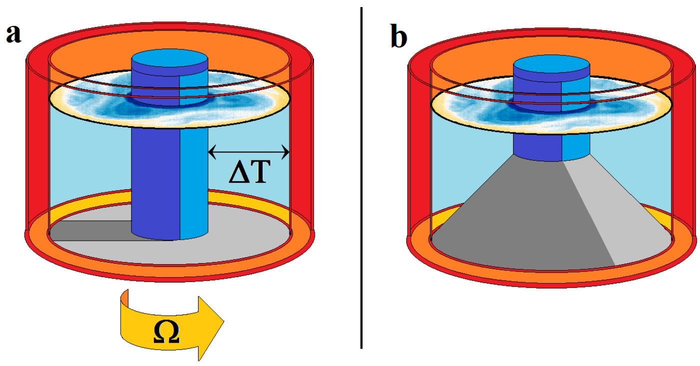

Figure 1. The schematic drawing of the geometry of our experimental setup in the flat bottom case (a) and with sloping bottom topography (b).

The ratio of the revolution period and the aforementioned hydrodynamical timescale yields an appropriate non-dimensional number for temperature-driven rotating systems, the thermal Rossby number Ro_T. For $Ro_T \gg 1$, the flow is axially symmetric and not significantly disturbed by rotation, whereas for $Ro_T \ll 1$ (as in the case of cyclones and and anticyclones in the atmosphere) the dynamics is dominated by the Coriolis effect. Another important non-dimensional parameter, the Taylor number Ta can be obtained similarly, by measuring the timescale of viscous effects with respect to the rotation period. Ro_T and Ta are widely used to characterise the different dynamical regimes in the rotating annulus.

Between the axially symmetric and geostrophic turbulent flow states there is a certain region in the $Ta - Ro_T$ plane where the velocity and temperature fields exhibit regular persistent wave-like patterns (see Fig.2a) that propagate along the azimuthal direction in the tank (Fig. 2b) due to *baroclinic instability*. Numerical methods ranging from primitive equation models to full-up direct numerical simulations have been used since the 1960s to reproduce the observed $Ta - Ro_T$ borderlines between these different regimes.

A recent numerical study based on a spectral model [1] investigated how the presence of a sloping bottom end wall (see: Fig. 1b) alters the aforementioned transition lines on the $Ta - Ro_T$ plane. We aimed to test and validate these numerical results in the BTU "reference setup". The flow patterns in the setup were observed by a co-rotating infrared camera, as in e.g. [4]. Spatial and temporal spectral analysis of the obtained thermographic data were used to classify the observed patterns. Space-time (aka Hovmöller) plots, as the ones in Fig.2 were also evaluated to distinguish between different flow regimes.

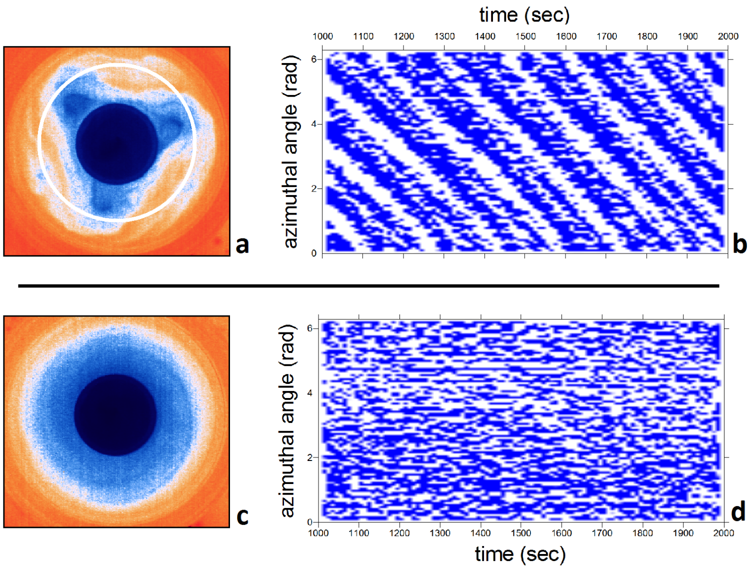

Figure 2. A thermal snapshot (a) and the propagation (Hovmöller) plot (b) of a stable regular wave at $Ta = 5.78 \cdot 10^6$, $Ro_T = 1.56$, and of a typical axisymmetric experimental run at $Ta = 3.57 \cdot 10^6$, $Ro_T = 2.55$ (c and d). The propagation plots depict the temporal development of temperature anomalies taken along the path marked by a white circle in (a). The white data points indicate warmer-than-average, while the blue depict colder-than-average temperature.

We concluded that the boundary that separates the axially symmetric and the "wavy" states shifted significantly once the sloping bottom topography was present. Also, a *transient region* has been clearly identified between these two regimes (both for flat and sloping endwalls) which seems to be relevant for characterising "phase transitions" in the system.

Hovmöller analysis revealed that in this transient region the waves exhibit strongly *nonlinear* behaviour, as their phase velocities – even for a given wavenumber and among the same boundary conditions – largely differed depending on their amplitude, i.e. the temperature anomalies associated with the waves. To the best of our knowledge, these nonlinear effects have not yet been studied systematically in the literature for this particular setup. The nonlinear coupling between the different wave modes has been found to be responsible for the observed differences between the numerical and experimental results.

The authors firmly believe that these findings will prove useful for testing and fine tuning atmospheric numerical models, and may contribute to the deeper understanding of transition phenomena in thermally driven rotating flows.

References

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