

Multi-mode states in quasi-two-dimensional rotating flows

Otto Chkhetiani, Alexey Gledzer, Evgeny Gledzer,
Maxim Kalashnik, and Alexey Khapaev

A.M. Obukhov Institute of Atmospheric Physics,
Russian Academy of Sciences, Moscow, Russia

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The idea of multiple equilibrium states of atmospheric circulation in geophysical hydrodynamics, and specifically, bimodality, goes back to (*Charney and DeVore 1979*), in which, using a model with a small number of variables and a finite-difference scheme with a relatively large number of degrees of freedom, solutions with significantly different values of zonal and wave speed components were obtained. The results of similar studies for low-parameter approximations were given in (*Kallen 1980, 1981; Glukhovsky et al. 2001; Koo and Ghil 2002*).

The regimes considered in these works differed in the magnitude of the zonal component of the flow (westward transport): in the state with weak transport, the role of almost stationary atmospheric eddies increases, which corresponds to the circulation blocking regimes.

In the same years, another kind of bimodality was found.

In experiments of A.M. Obukhov and co-workers (*Obukhov et al. 1976*, *Gledzer et al. 1981*), modes with differently directed axes of large-scale fluid rotation were observed in closed vessels with the same value of external generation of hydrodynamic currents.

The analog of transitions between the above modes for atmospheric circulation could be a finite-angle shift of the system of cyclones and anticyclones, which leads to significant climatic changes in conditions of inhomogeneity of the Earth's surface.

Another type of multimode can be related to the existence of quasi-stationary states with different wave numbers of disturbances specifying cyclonic and anticyclonic vortices of the atmospheric circulation under the same external parameters.

In this paper, the above types of multi-mode, are considered on the basis of laboratory and numerical experiments in circular rotating channels. In some of our previous works in this direction (2014-2020), the permanent magnet (or source-stock) configurations could create a nearly stationary distribution of cyclonic and anticyclonic vortices.

This creates the possibility of finding different equilibrium states under the same external parameters generating fluid motion in the channel.

In this case, as in the mentioned experiments of A.M. Obukhov and collaborators, the transition between different states is provided by changing the value of the main parameter of generation of currents (for MHD currents - current between electrodes on the outer and inner radii of the channel) with subsequent restoration of its initial value.

Introduction

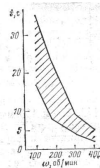
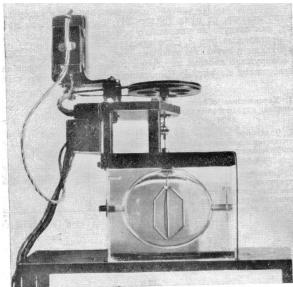
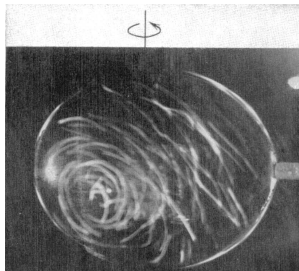
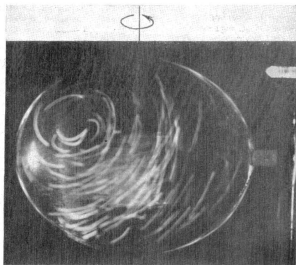


Рис. 6. Осуществление переброса в зависимости от продолжительности отключения внешней силы. Заштрихованная область отвечает моментам времени, когда включение мешалки приводит к перебросу. Отсчет времени ведется от момента ее отключения.



The phenomenon of flipping. A.M. Obukhov et al.

Introduction

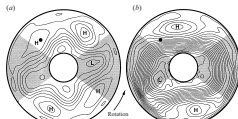
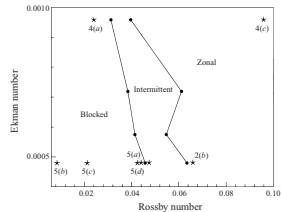
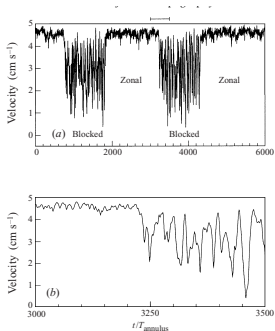
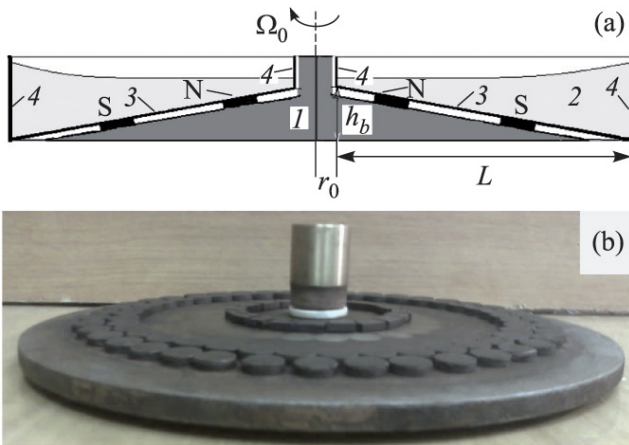


FIGURE 2. Time-averaged streamfunction field for (a) blocked and (b) zonal flow. The streamfunction is calculated from the velocity field measured by particle tracking. The shaded areas indicate the coverage of the mountains, and the black dot indicates the position of the hot-dim probes. The contour interval is $15 \text{ cm}^2 \text{ s}^{-1}$ for both streamfunctions, and the letters H and L indicate the highs and lows of the streamfunctions. The Rossby numbers Ro for the blocked and zonal flows are 0.044 ± 0.004 and 0.066 ± 0.004 respectively (pump flux $F = 280$ and $390 \text{ cm}^3 \text{ s}^{-1}$); for both flows, the Ekman number is $Ek = 4.8 \times 10^{-4}$ ($\Omega = 3\pi \text{ rad s}^{-1}$).



Transitions from zonal to blocked mode in the experiments of *Weeks et al. 1997*; *Tian et al. 2001*.

Schematic diagram of a laboratory setup

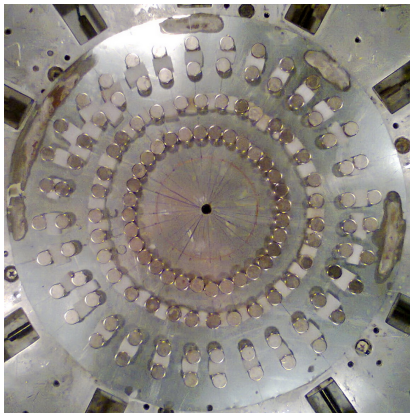


$$T \sim 2 \text{ sec} \div 1 \text{ min}; s = h_b / (R_{out} - R_{in}) = 0.038$$

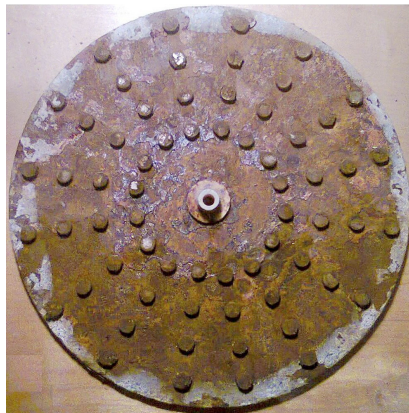
$$1. R_{in} = 1.5 \text{ cm}; R_{out} = 14 \text{ cm}$$

$$2. R_{in} = 5.5 \text{ cm}; R_{out} = 18 \text{ cm}$$

Magnet configurations

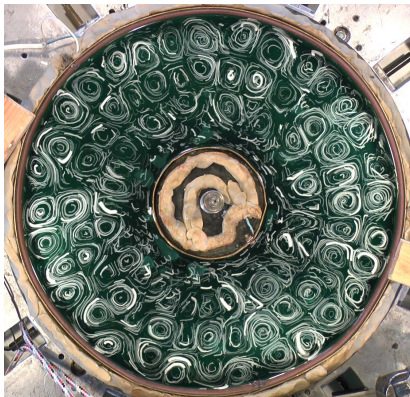


Channel 2



Channel 1

Basic small-scale motion



Marker trajectories: channel 2, 10
mm, $T=4.1$ сек.

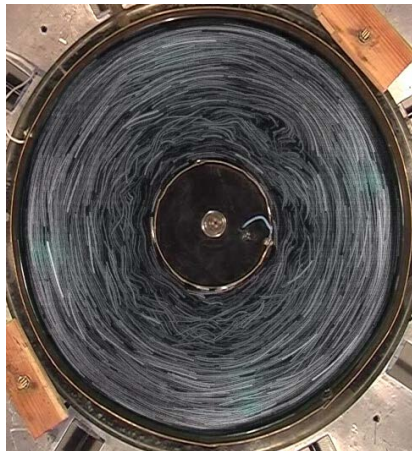


Marker trajectories: channel 1, 10
mm, $T=5.3$ сек.

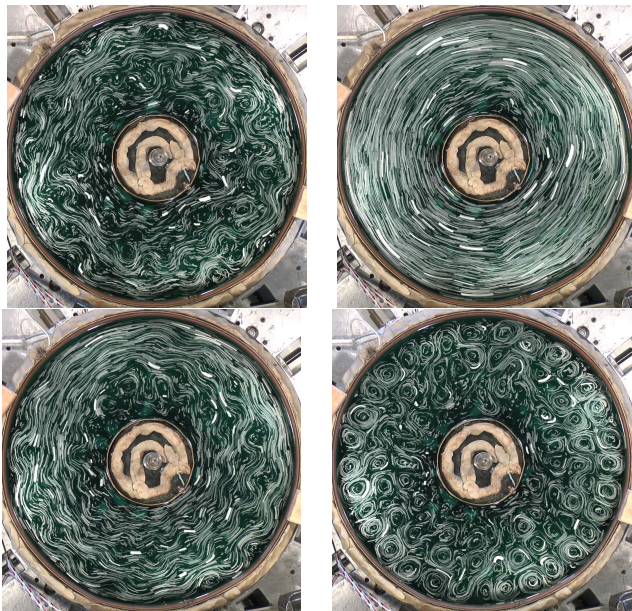
Overflights to ring vortices. $h=10$ mm, $T=4.7$ sec.



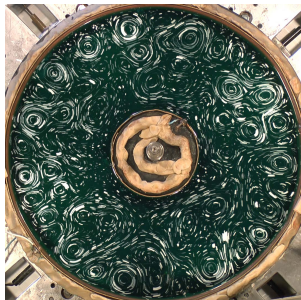
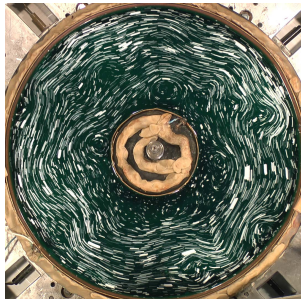
Overflights to ring vortices. $h=10$ mm, $T=5.8$ sec.



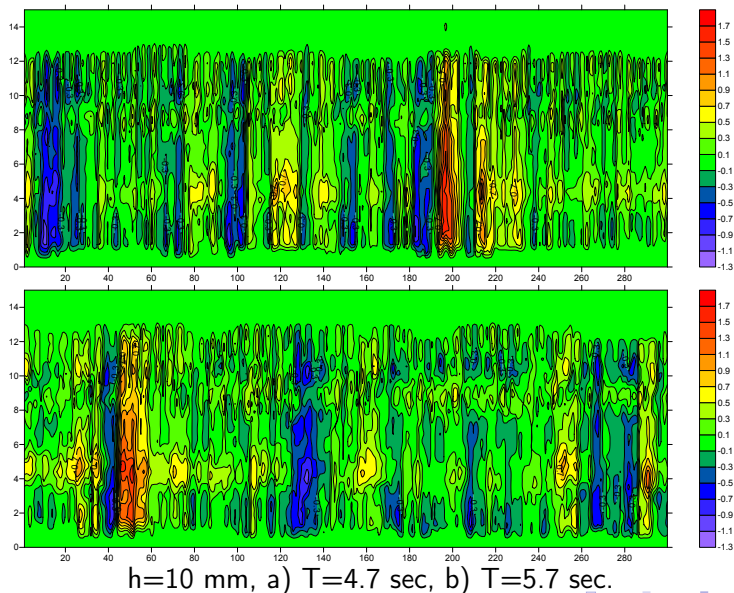
Overflights($T=8.3$ sec, $h=15$ mm, $I=900$ mA)



Overflights ($T=60$ sec, $h=20$ mm, $I=900$ mA)



Overflights to ring vortices – azimuthal velocity



magnets with a diameter of 15 mm and a height of 10 mm with an average magnetic induction of 0.358 Tesla per magnet were arranged along circles with radii of 7 and 13 cm (for channel 1) and 15 and 26 cm (for channel 2).

Polarity of the direct electric current supplied through the electrodes provided at the initial moment of time after switching it on the opposite to the external rotation of the conducting liquid near the outer border of the channel.

This corresponds to a **Eastern** equatorial wind.

In this case, in the middle part of the channel, the fluid moves in the same direction as the external rotation (western midlatitude transport).

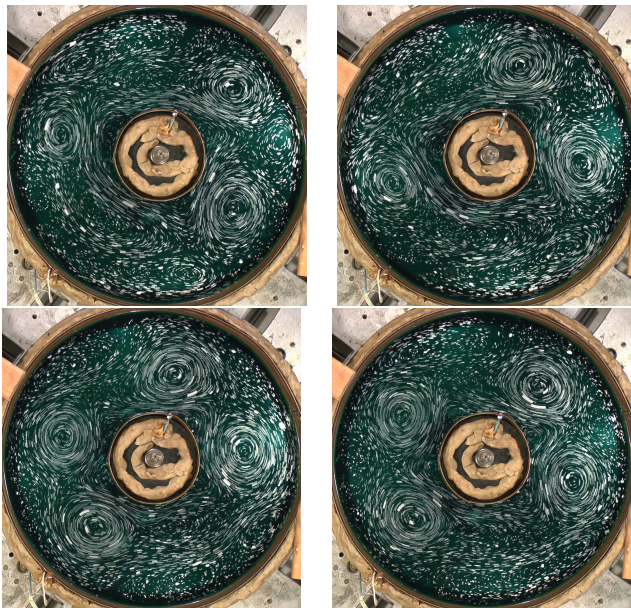
The scheme of the experiments is as follows:

After the current is turned on (500 mA) for 2 minutes, the fluid flow regime is established in the channel, with a certain amount of cyclonic and anticyclonic eddies, standing or weakly carrying them along the azimuthal angle.

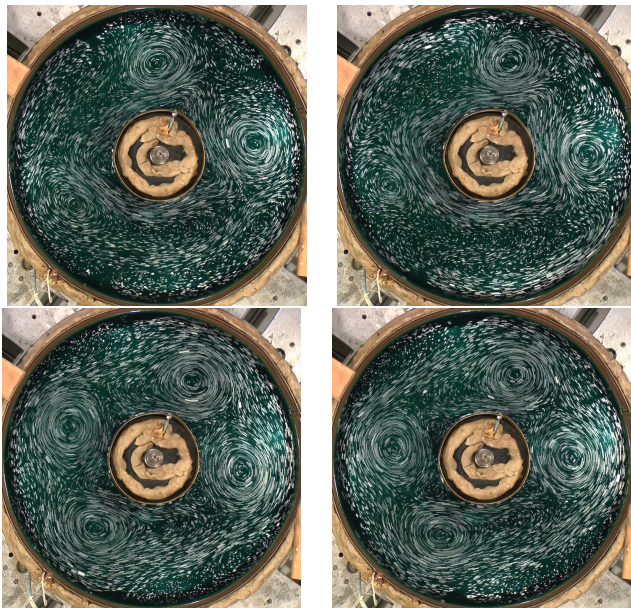
Then for the next 2 minutes, the current is increased to 700 mA to destroy or significantly alter the flow regime formed in the previous 2 minutes. Note that in the experiments mentioned above (Obukhov et al.) the external action on the fluid was **actually switched off**.

After 2 minutes with a current of 700 mA, the previous current of 500 mA was switched on, i.e., the external parameters returned to their previous values, only the initial conditions of current generation changed. can expect either **return** to the mode of the first two minutes of the experiment for configurations of cyclonic and anticyclonic vortices, or **transition** to a significantly **excellent** current by the location of vortices or their number.

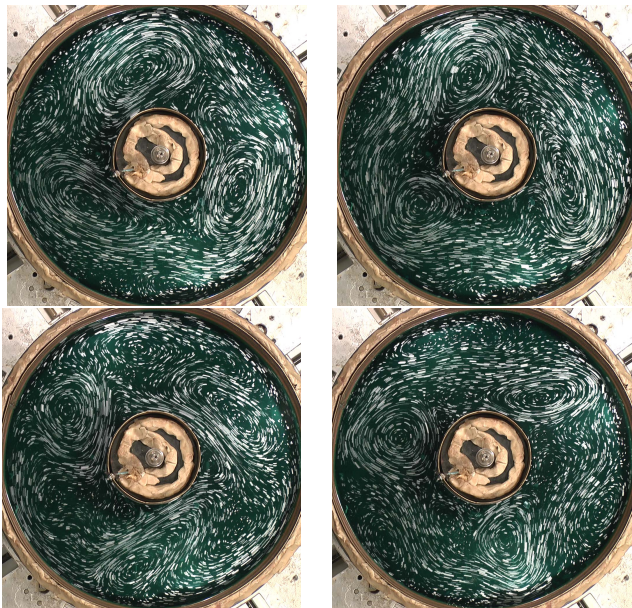
Particle trajectories, $t=0.5\text{min}$, 2min , 5.5min , 6.0min . $T=8.2\text{ sec}$.



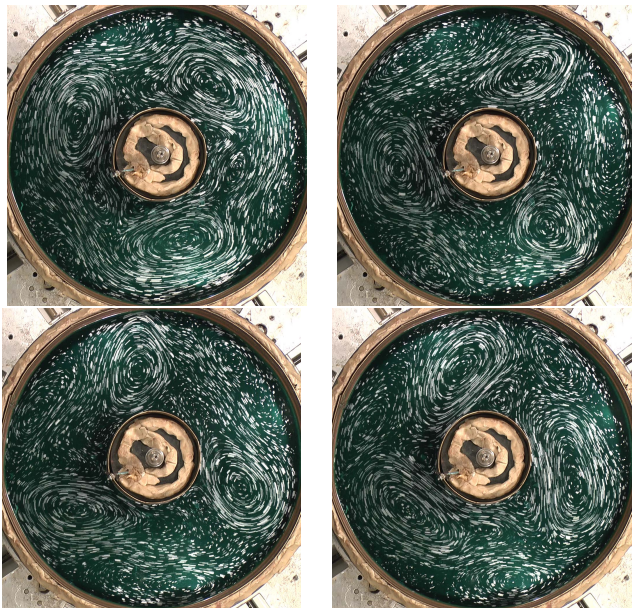
Particle trajectories, $t=0.5\text{min}$, 2min , 5.5min , 6.0min . $T=7.3\text{ sec}$.



Particle trajectories, $t=0.5, 2, 5.5, 6.0$ min. $T=20.3$ sec.



Particle trajectories, $t=0.5, 2, 5.5, 6.0$ min. $T=17.7$ sec.



Experimental results show that for some values of the parameters, transitions to different modes from the initial ones are possible:

- For fast rotations, the number of anticyclonic vortices changes.
- For slower rotations, while the number of anticyclonic vortices remains unchanged, their angular position has changed significantly.
- For intermediate periods, there were no transitions to new modes, and the final vortex motion patterns were virtually the same as the initial ones.
- All experiments were performed while changing the main parameter of generation: for the laboratory experiments this is an increase in current from 500 mA to 700 mA followed by a return to 500 mA.

- Numerical experiments with the shallow water model confirm the results on the possibility of transition to new regimes when the parameter determining the external force on the fluid during MHD generation and generation of flows by the source-stream method is changed for some time.
- A possible reason is the introduction of noise into the initial stationary picture of the flow, which creates the possibility of transition to new modes with the help of mechanisms of induction of transitions by noise.
- This mechanism may be an alternative to low-mode scenarios in the multi-mode problem.

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