

Турбулентность, вихри, струйные течения и структурные переходы в квазигеострофических гидродинамических экспериментах

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Turbulence, vortices, jet streams, and structure transitions in quasi-geostrophic hydrodynamic experiments



A.M. Obukhov, G.S. Golitsyn, F.V. Dolzhansky, M.V. Kurgansky, Y.L. Chernous'ko and R. Hide. 1978



A.M. Obukhov, F.V. Dolzhansky, E.B. Gledzer, F.V. Dolzhansky. 1979

Structures and flows of planetary scales have always been one of the central problems of geophysical hydrodynamics, taking into account the study of such formations in the atmospheres of the Earth and the planets.

These include large eddies on giant planets, zonal currents in the Earth's atmosphere at mid-latitudes, jet flows in the atmosphere and associated meanderings and ocean rings.

In the atmospheres of the Earth and planets, such structures have been known for a long time and in the ocean extended submesoscale structures have been discovered relatively recently.

In addition, it should be especially said about blocking formations. This type of motion includes systems of counter-current zonal flows in planetary atmospheres demonstrating both super-rotational and subrotational behavior.

In an ideal two-dimensional hydrodynamics, the explanation of the enlargement of vortex formations and extended flows from small-scale turbulent perturbations of the velocity field should not cause difficulties, since the mechanism of the inverse cascade of energy with appropriate energy transfer to the large-scale interval of the scale spectrum is known.

But already for relatively thin layers, where vertical motions are permissible, the mechanism of reverse energy transfer is not fully clarified.

As the results of experiments for thin layers show, as well as measurements of the velocity field in the atmosphere, the three-dimensionality of the flows proves to be an important factor in the dynamics, which is manifested in particular in the transition of the longitudinal structure functions of the third-order velocity field to negative values (as in three-dimensional turbulence).

The results of experiments in circular non-rotating and rotating channels in thin fluid conductive layers for configurations consisting of a large number of permanent magnets and providing MHD generation of small-scale velocity fields are presented.

The alternating ray configurations of the magnets were chosen in such a way as to ensure the preservation of the discrete symmetry of their relative position relative to the rotary channel rotations about the central axis and were formed on the basis of numerical calculations with the shallow water equations.

Both in numerical and in laboratory experiments, large-scale almost circular vortices were obtained as a result of energy transfer from a system of externally generated small-scale vortices to large-scale velocity fields (the inverse cascade) under the influence of the Coriolis force in the case of rotation.

Single large-scale eddies and wide jet streams appear in the modes of subrotation and superrotation with respect to external rotation.

The anisotropization – B. Galperin et al. OD 2007, S.Espa et al. 2014 JPO 2014; B.Galperin et al. PRE 2016

The homogenization of potential vorticity – Rhines, Young JFM 1982, Auberf et al. GRL 2002, Constantinou et al. JAS 2014

The vortex condensate – Xia et al. PRL 2008, PF 2009; Bardóczy et al.

Changes in the sign of structural functions – Naström, Gage JAS 1985, Gledzer et al. JETP 2011

Since 70-th... A.M.Obukhov, F.Dolzhanovsky, E.Gledzer, Yu.Novikov, M. Chusov, V. Ponomarev, Yu. Chernous'ko, M. Kurgansky, B. Boubnov, V. Dovzhenko, V. Krymov, A. Batchaev, G. Golitsyn, D. Manin, S. Danilov, I. Sazonov, I. Yakushkin, A. Khapaev, S. Kostykin, A. Gledzer....

Hydrodynamic stability; Elliptic instability, Convection, Rossby waves, Blocking phenomena, Bottom and Ekman friction, Clusters formation, Self-oscillations processes, Kolmogorov flow, 2D and Quasi-2D stationary and decaying turbulence...

Inertial method, Source-Sink method, MHD-method, PIV, Numerical pre-modelling...

ФИЗИКА АТМОСФЕРЫ И ОКЕАНА
Том 12 1974 № 2

УДК 551.511

ИССЛЕДОВАНИЕ УСТОЙЧИВОСТИ ДВИЖЕНИЯ ЖИДКОСТИ ВНУТРИ ТРЕХОСНОГО ЭЛЛИпсоИДА

Е. В. ГАЛДУЗЕР, Ю. В. ВОЛНЕНКО, А. М. ОБУХОВ, М. А. ЧУСОВ

Дано строгое установившееся движение вращающейся жидкости в трехосном эллипсоиде. Проведены расчеты устойчивости, выходящая из этой установки. Получены теоретические кривые зависимости критического значения скорости от эллипсоидности и асимметрии эллипсоидного движения. Обсужден инерционный эффект вращающейся жидкости в эллипсоиде. Приведены результаты приближенного теоретического расчета диаграммы устойчивости для эллипсоидов.

ФИЗИКА АТМОСФЕРЫ
И ОКЕАНА
Том 15 - № 6
1979

УДК 551.5

ЛАБОРАТОРНОЕ И ТЕОРЕТИЧЕСКОЕ ИССЛЕДОВАНИЕ БАРОТРОННЫХ ВОЛН РОСКИ В ВРАЩАЮЩЕМСЯ КОЛЬЦЕВОМ КАНАЛЕ

Ф. В. ДОЛЖАНСКИЙ, М. В. КУРТАНСКИЙ, Ю. З. ЧЕРНОВСКОЕ

Выполнено экспериментальное и теоретическое исследование устойчивости баротронных волн Роски во вращающемся кольцевом канале. При определенных условиях наблюдались волны с азимутальным числом $m=2$. Результаты экспериментального исследования в удовлетворительном согласии с теоретическими, полученными на базе уравнений гидродинамической модели.

ФИЗИКА АТМОСФЕРЫ
И ОКЕАНА
Том 12 - № 11
1976

УДК 551.511:532.5

О ЯВЛЕНИЯХ ПЕРЕБОРА В ПРОСТРАНСТВЕННЫХ ГИДРОДИНАМИЧЕСКИХ СИСТЕМАХ

А. М. ОБУХОВ, А. Б. ГЛУХОВСКИЙ, Ю. З. ЧЕРНОВСКОЕ

Для простейшей гидродинамической системы (вращающегося цилиндра) исследованы внутри аксиальной плоскости, возникающей при определенных начальных условиях, волны развития стационарных течений. Рассмотрены устойчивость, порождая между ними путем комплексного отклонения волновой скалы. Приводятся результаты экспериментальных исследований.

ФИЗИКА АТМОСФЕРЫ
И ОКЕАНА
Том 15 - № 11
1979

КРАТКОЕ СООБЩЕНИЕ

УД

МОДЕЛИРОВАНИЕ ПРОЦЕССА ГЕНЕРАЦИИ ВИХРЕЙ В АКСИАЛЬНО СИММЕТРИЧНОМ АЗИМУТАЛЬНОМ ПОЛЕ МАГНИТОГИДРОДИНАМИЧЕСКИМ МЕТОДОМ

В. А. ДОЛЖАНСКОЕ, Ю. В. ВОЛНЕНКО, А. З. ОБУХОВ

Вестник
МОСКОВСКОГО УНИВЕРСИТЕТА
№ 5 — 1976

УДК 532.013.6

Н. Ф. ГОРШКОВ, А. М. ОБУХОВ

О ГЕНЕРАЦИИ ВИХРЕВЫХ ВОЗМУЩЕНИЙ ПРИ ЭЛЛИПТИЧЕСКОМ ВРАЩЕНИИ ЖИДКОСТИ

Описывается простейший механический способ генерации вихревых возмущений, который может быть использован при исследовании турбулентности процессов.

МЕХАНИКА
ЖИДКОСТИ И ГАЗА
№ 4 - 1981

УДК 532.51.011

О ГЕНЕРАЦИИ ВИХРЕЙ В АКСИАЛЬНО-СИММЕТРИЧНОМ СДВИГОВОМ ТЕЧЕНИИ

ДОЛЖАНСКОЕ В. А., ОБУХОВ А. М., ПОНОМАРЕВ В. М.

ФИЗИКА АТМОСФЕРЫ
И ОКЕАНА
Том 15 - № 10
1979

УДК 532.529.2 : 533

ЛАБОРАТОРНАЯ И ТЕОРЕТИЧЕСКАЯ МОДЕЛИ ПЛОСКОГО ПЕРИОДИЧЕСКОГО ТЕЧЕНИЯ

Н. Ф. ДОЛЖАНСКОЕ, М. З. ГАК, Ф. В. ДОЛЖАНСКИЙ

Приводятся результаты лабораторного и теоретического исследования плоского периодического течения, возникающего в вихревых каналах. Результаты экспериментального исследования в хорошем качественном согласии с теоретической моделью плоского периодического течения, предположенной ранее. Основан на численном решении уравнений Навье-Стокса. Кроме того, в экспериментах наблюдались неустойчивости, предположительно вызванные эффектом неустойчивости по отношению к вихревым каналам, что противоречит линейной теории неустойчивости периодического течения, рассмотренной в [1, 2]. Поэтому предлагается модифицированную модель рассматриваемого течения с учетом влияния неустойчивости вихревых каналов, позволяющую объяснить в эксперименте описанные экспериментальные результаты.

Известия АН СССР
ФИЗИКА АТМОСФЕРЫ
И ОКЕАНА
Том 17 - № 1
1986

УДК 551.511.32

О НЕУСТОЙЧИВОСТИ ПЕРИОДИЧЕСКОГО СДВИГОВОГО ТЕЧЕНИЯ СЛАБОАТРАФИЦИРОВАННОЙ ЖИДКОСТИ

БАТЧАЕВ А. М., КУРТАНСКИЙ М. В.

Проведено лабораторное моделирование слабоатрафического сдвигового течения в слабоатрафической жидкости (при значении числа Рейнольдса $Re \leq 1$), возбуждаемого магнитогидродинамическим методом периодического распределения в пространстве вихревых каналов. На основе строгих расчетов приводятся к значительному укреплению критического значения течения. Результаты численного исследования критического значения течения (для аналогичного течения односторонней асимметрии Re), причем при сдвиге стратификации ($Re = Re_0$)/ Re_0 прямо пропорционально квадрату частоты Брэгга - Вайсера. Обнаружено удовлетворительное согласие с теоретической формулой ($Re = Re_0$)/ $Re_0 = 1/2$, полученной с учетом течения жидкости с вихревыми каналами.

Since 1972, the Laboratory of Geophysical Hydrodynamics has published 116 articles and 3 monographs on the topic of laboratory modeling of geophysical flows.

The idea of multiple equilibrium states of atmospheric circulation in geophysical hydrodynamics, and specifically, two-modality, dates back to (Charney, DeVore 1979).

Here, for 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 the zonal and wave components of velocity were obtained.

The results of similar studies for low-parameter approximations were presented in (Kallen 1980, 1981; Glukhovskiy et al. 2001; Koo, Ghil 2002).

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

In the same years, another kind of two-modality was found.

In experiments conducted by A.M. Obukhov and his collaborators (Obukhov et al. 1976, Gledzer et al. 1981), modes with multidirectional axes of large-scale rotation of a liquid with the same magnitude of external generation of hydrodynamic flows were observed in closed vessels.

An analogue of the transitions between these modes for atmospheric circulation could be a shift to the final angle of the system of cyclones and anticyclones, which, in conditions of heterogeneity of the Earth's surface, leads to significant climatic changes.

Another type of multimode can be associated with the existence of quasi-stationary states with different wavenumbers of disturbances that define cyclonic and anticyclonic vortices of atmospheric circulation with the same external parameters.

In this paper, the types of multimode are considered on the basis of laboratory and numerical experiments in annular rotating channels.

In a number of our previous works in this area (2014-2019), the configurations of permanent magnets (or sink sources) could create an almost stationary pattern of distribution of cyclonic and anticyclonic vortices.

This makes it possible to search for different equilibrium states with the same external parameters that generate fluid movement in the channel.

At the same time, as in the mentioned experiments by A.M. Obukhov and his collaborators, the transition between different states is ensured by changing the value of the main parameter of current generation (for MHD currents, the current between the electrodes on the outer and inner radii of the channel), followed by restoring its initial value.

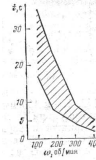
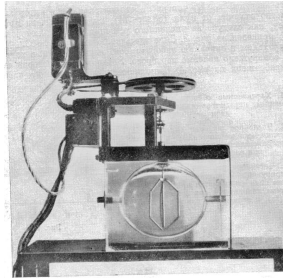
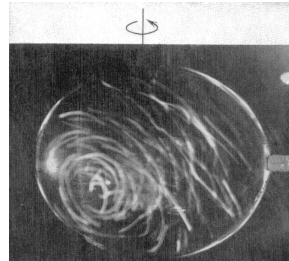
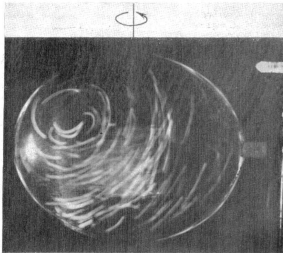


Рис. 6. Осуществление переброса в зависимости от продолжительности отключения внешней силы. Заптрихованная область отвечает моментам времени, когда включение мешалки приводит к перебросу. Отсчет времени ведется от момента ее отключения



The phenomenon of transfer between stationary modes. A.M. Obukhov et al.

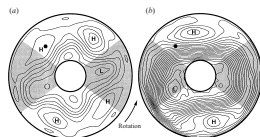
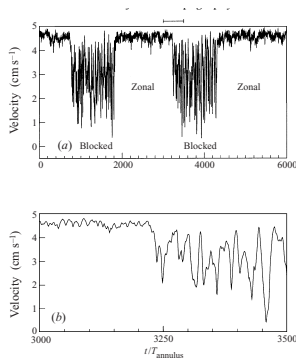
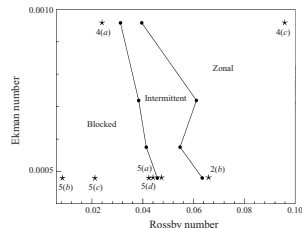
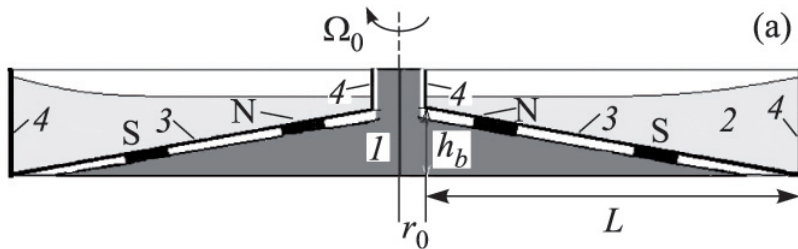


FIGURE 2. Time-averaged streamfunction field for (a) blocked and (b) zonal flow. The streamfunction is calculated from the velocity field measured by particle tracking. The shaded areas indicate the coverage of the mountains, and the black dot indicates the position of the hot-film probes. The contour 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 $F = 260$ and $390 \text{ cm}^3 \text{ s}^{-1}$); for both flows, the Ekman number is $Ek = 4.8 \times 10^{-6}$ ($\Omega = 3 \text{ rad s}^{-1}$).

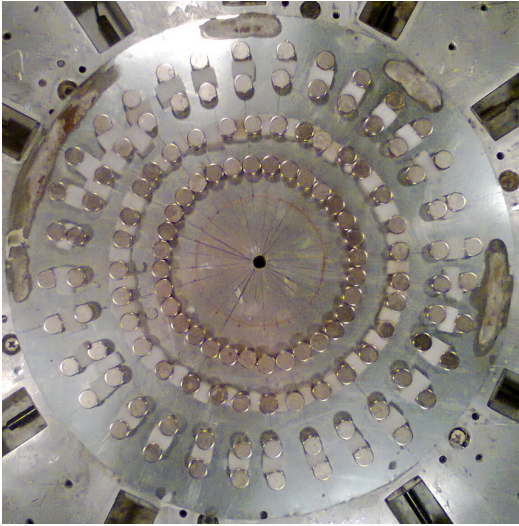


Transitions from the zonal mode to the blocked one in experiments Weeks et al. 1997; Tian et al. 2001.

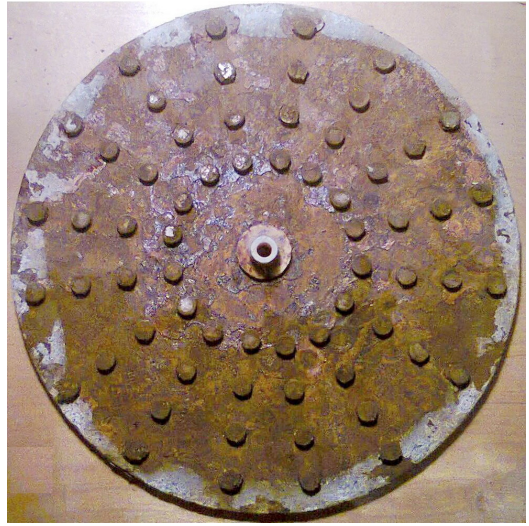


$$T \sim 2 \text{ sec} \div 1 \text{ min}; s = h_b / (R_{out} - R_{in}) = 0.038$$

Magnet configurations

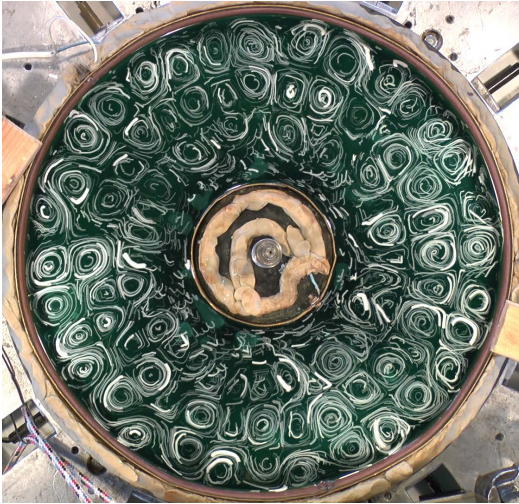


The channel 2



The channel 1

The basic small-scale motions



Marker paths: channel 2, 10 mm, $T=4.1$ sec.

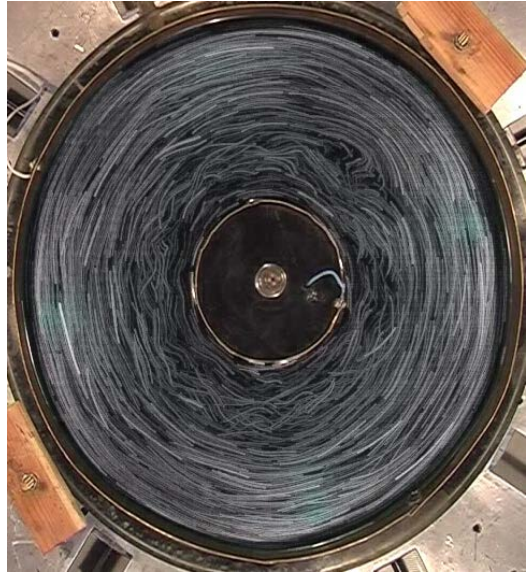


Marker paths: channel 1, 10 mm, $T=5.3$ sec.

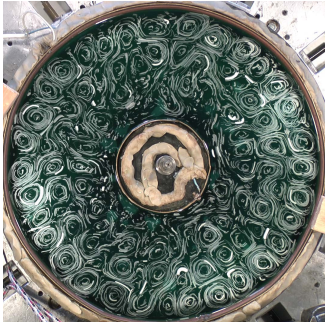
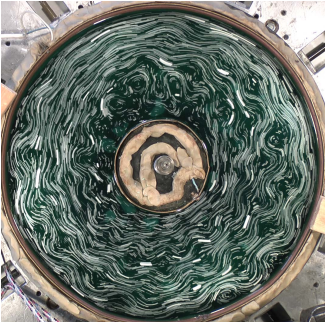
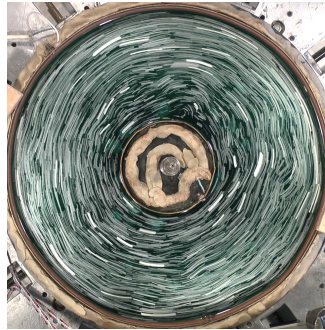
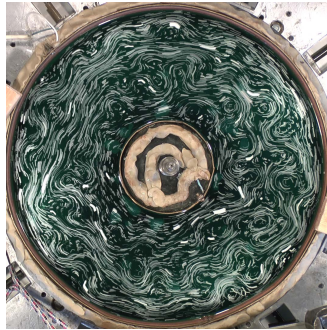
Transitions to the circular vortices. $h=10$ mm, $T=4.7$ sec.



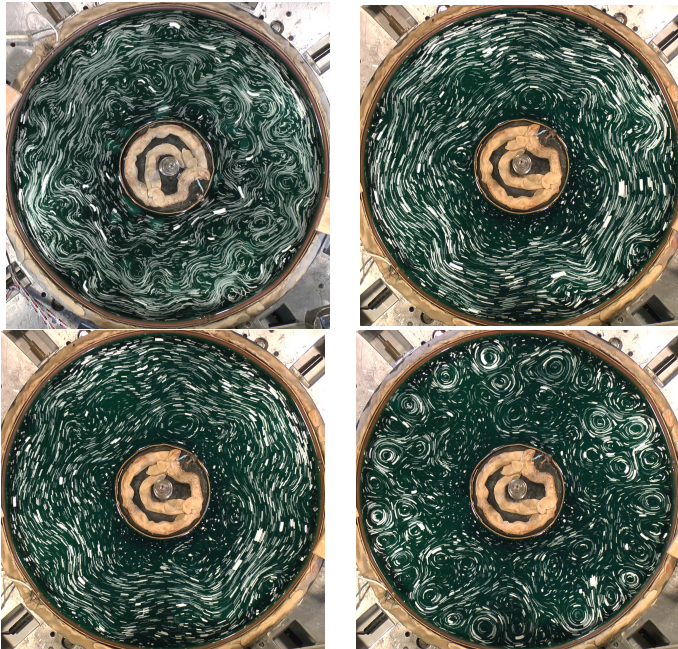
Transitions to the circular vortices. $h=10$ mm, $T=5.8$ sec.



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



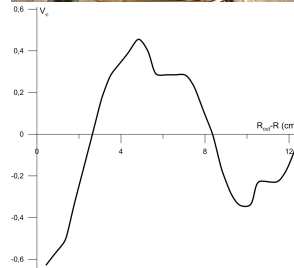
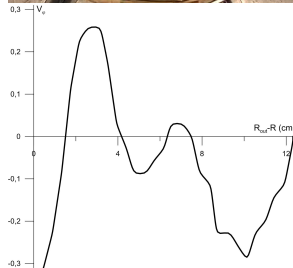
Transitions ($T=60$ sec, $h=20$ mm, $I=900$ mA)



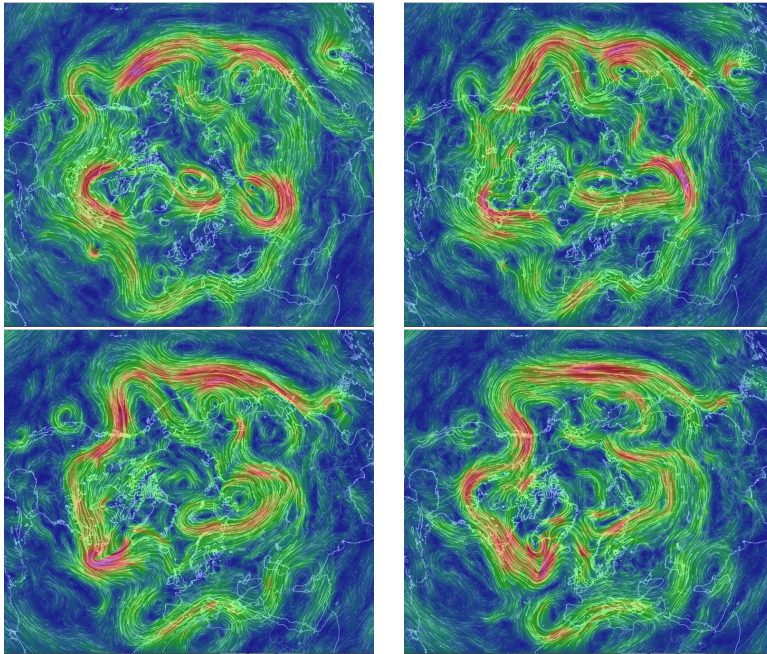


Particle trajectories during generation of vortices with formation of clusters by shear flow in channel 1:
(a) $T=15.4$ sec; (b) another current direction $T=15.4$ sec; (c) $T=19.1$ sec.

Jet flows with vortices

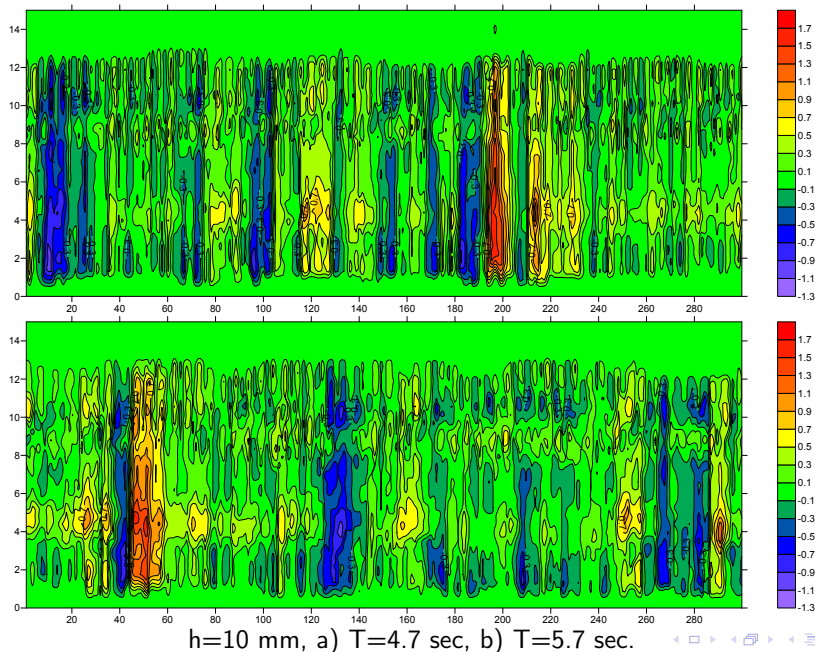


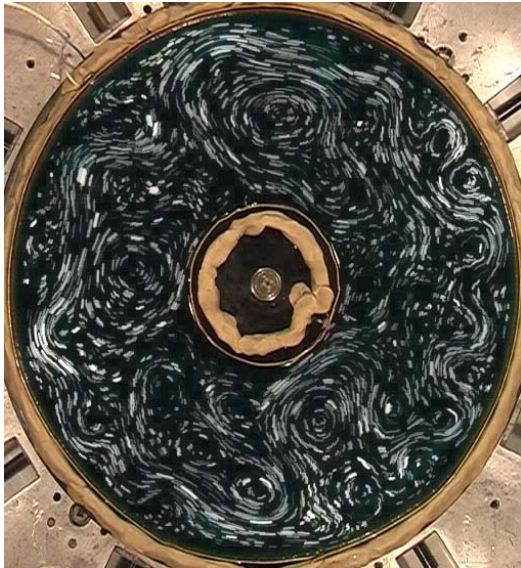
a) $T=29.4$ sec, $h=15$ mm; b) $T=24.4$ sec, $h=24$ mm.



The jet flows of the northern hemisphere in the wind field at the level of 500 mbar: a) 18.09.14; b) 19.09.14; c) 20.09.14; d) 21.09.14 are presented in the azimuthally equidistant projection

Transitions to the circular vortices – azimuthal velocity



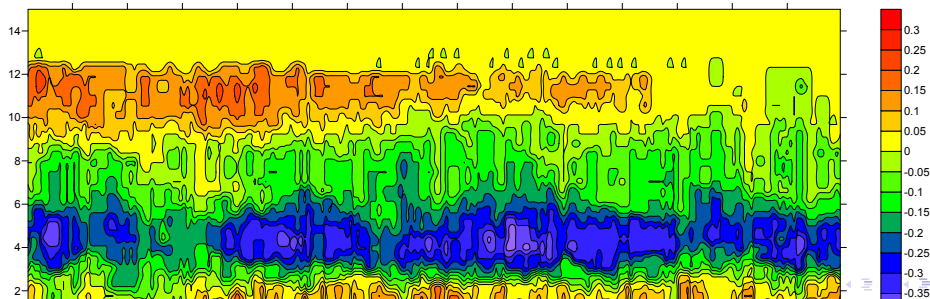
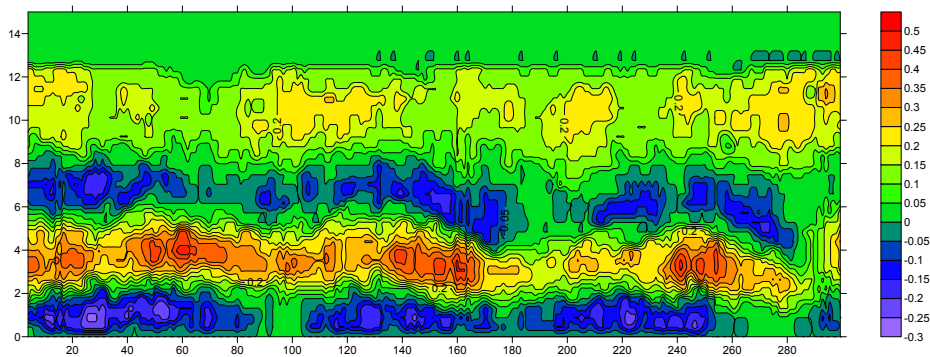


Well defined narrow jet flows, channel 2: a) $h=24$ mm, $T=67.0$ sec, b) $T=39.8$ sec, $h=24$ mm.

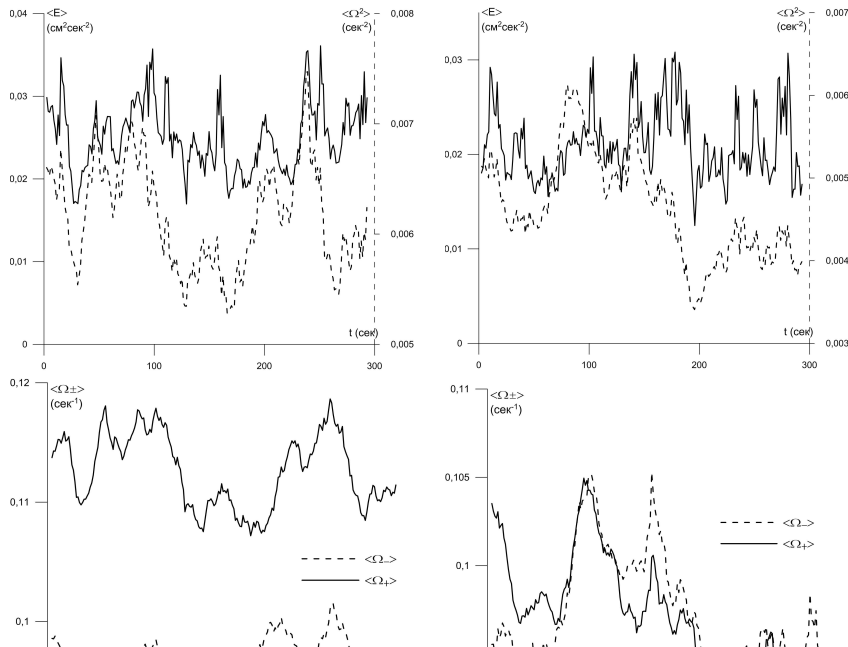


The jet flow in channel 2 (T=39.8 sec, $h=24$ mm) at different instants of time.

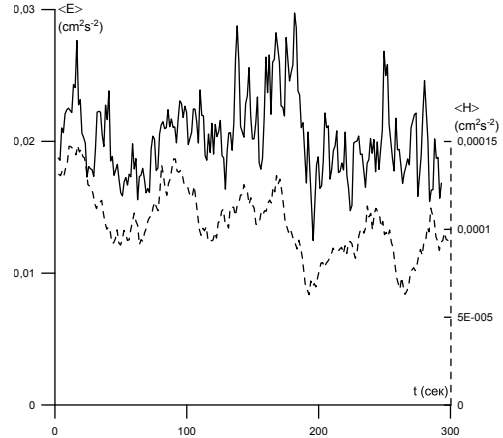
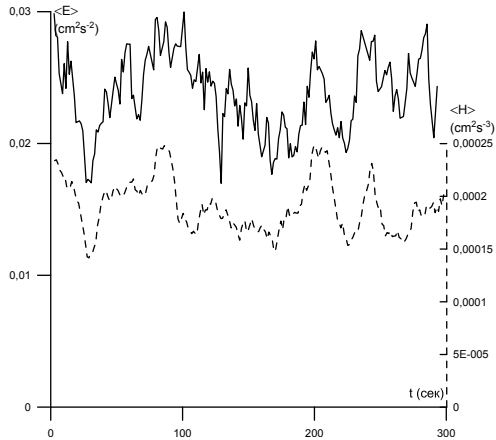
Jet flows - azimuthal velocity dynamics



Energy, enstrophy and vorticity: T=39.8, 67 sec; h=24 mm



Helicity estimations: $T=39.8, 67$ sec; $h=24$ mm



$$v_z \sim -h \operatorname{div}_{\perp} \mathbf{v}, \quad H = v_{\perp} \operatorname{curl}_{\perp} \mathbf{v} + v_z \operatorname{curl}_z \mathbf{v}$$

Cylindrical neodymium magnets with a diameter of 15 mm and a height of 10 mm with an average magnetic induction value of 0.358 Tl for each magnet were located along circles with radii of 7 and 13 cm (for channel 1) and 15 and 26 cm (for channel 2).

The polarity of the direct electric current supplied through the electrodes ensured, at the initial moment of time after its inclusion, the opposite rotation of the conductive liquid near the outer boundary of the channel with respect to the external one.

This corresponds to the **east** equatorial wind.

At the same time, in the middle part of the channel, the liquid moves in the same direction as the external rotation (the western transfer of the middle latitudes).

The scheme of experiments

The scheme of experiments is the next:

After switching on the DC current (500 mA) for 2 minutes, the mode of fluid movement in the channel is set, with a certain number of cyclonic and anticyclonic vortices, standing or with weak transmission along the azimuth angle.

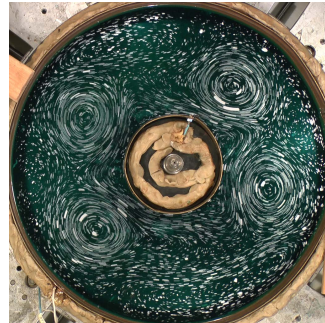
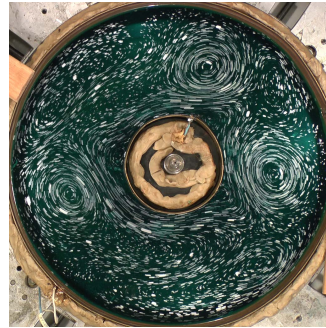
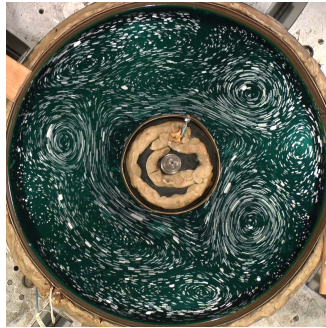
Then, for the next 2 minutes, the current increases to 700 mA in order to disrupt or significantly change the flow regime formed in the previous 2 minutes.

Note that in the experiments mentioned above (Obukhov et al.), the external effect on the liquid **was turned off altogether**.

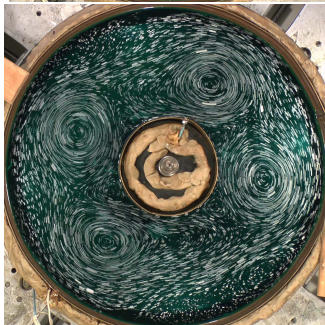
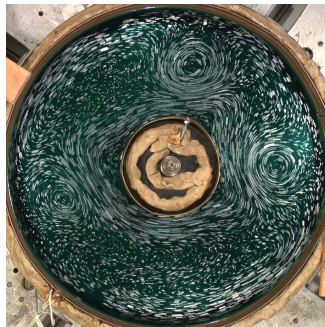
After 2 minutes of operation with a current of 700 mA, the previous current of 500 mA was switched on, i.e. the external parameters returned to their previous values, only the initial conditions of current generation changed.

One can expect either a **return** to the mode of the first two minutes of the experiment for the configurations of cyclonic and anticyclonic vortices, or a **transition** to a significantly **different** flow in

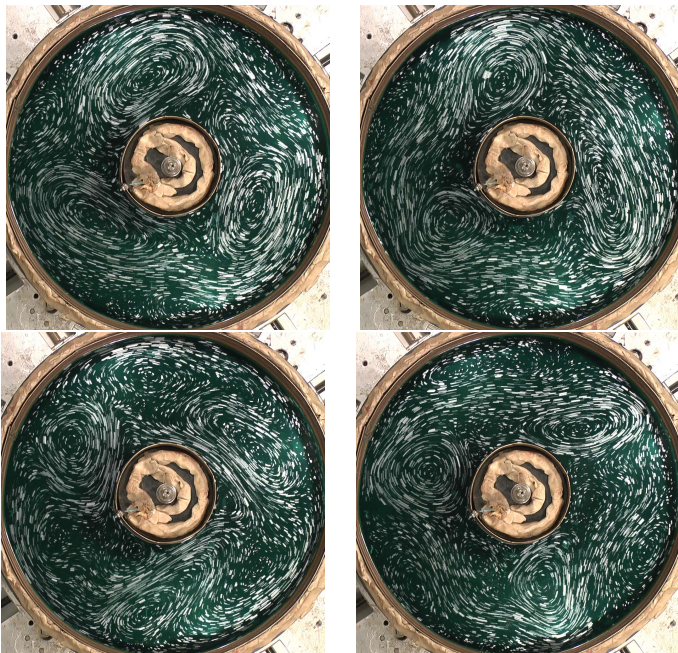
Particle trajectories, $t=0.5$ min, 2 min, 5.5 min, 6.0 min. $T=8.2$ sec.



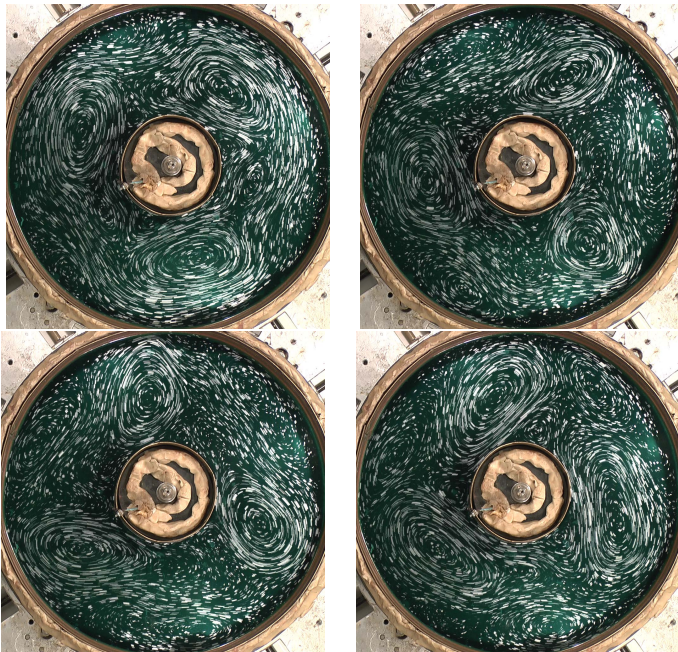
Particle trajectories, $t=0.5$ min, 2 min, 5.5 min, 6.0 min. $T=7.3$ sec



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



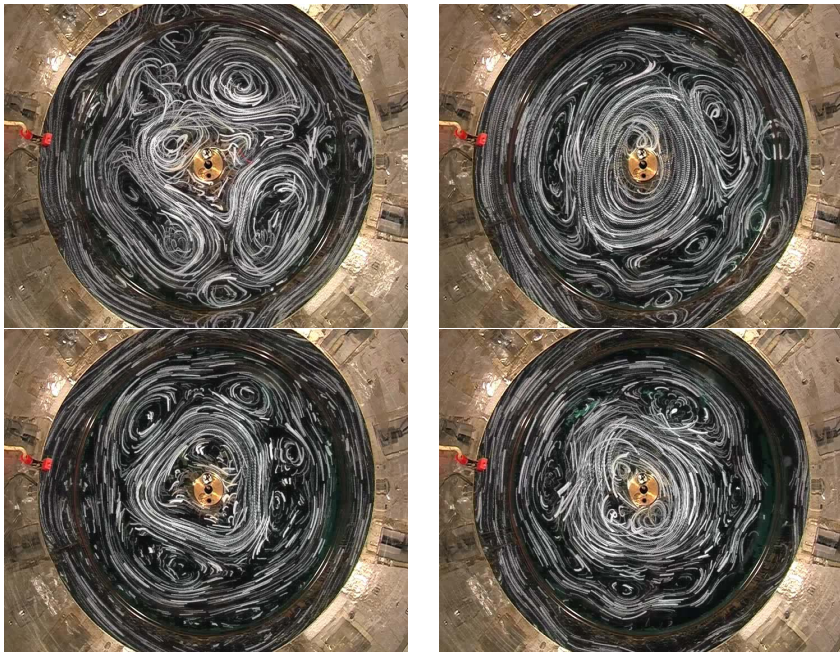
Particle trajectories, $t=0.5, 2, 5.5, 6.0$ min. $T=17.7$ sec.



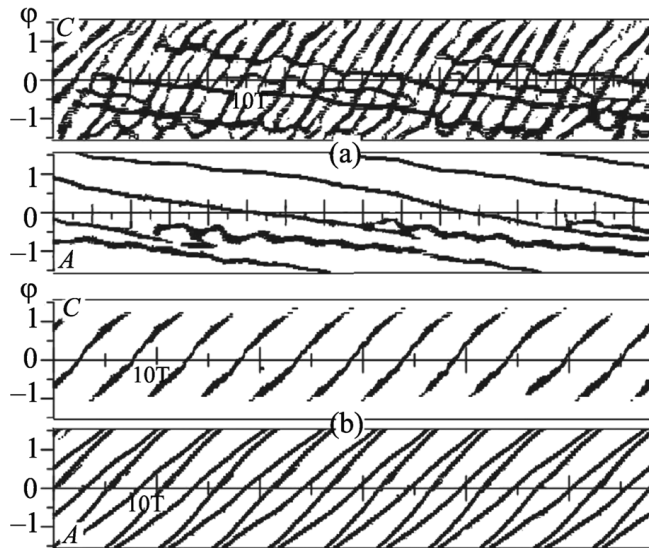
Marker trajectories in the observed flows



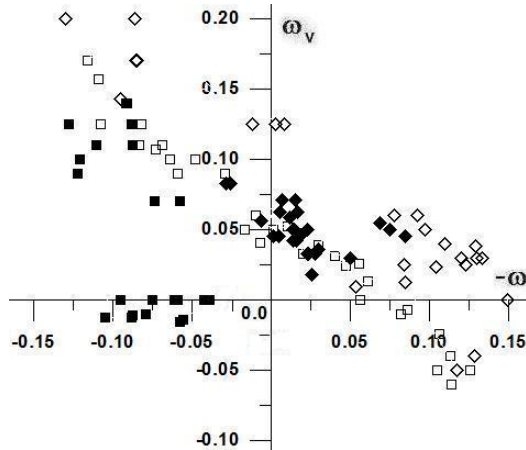
Marker trajectories in the observed flows



Time dependence of the angular coordinates φ of the (C) cyclones and (A) anticyclones



Parameters ω and ω_V for the experiments with the (filled symbols) and MHD generation and (open symbols) sources and sinks



$$\omega_v = \frac{d\varphi_v}{d(|\Omega_0|t)}$$

- An experimental MHD technique for the beta-plane experiments has been developed.
- For the fast rotation regimes with a thin fluid layer, where the Rossby–Obukhov scale does not exceed the characteristic sizes of the annulus, the system of perturbations appears with almost immobile blocked anticyclones in the outer part of the flow and rapidly moving cyclones in the main flow.
- The diagram of regimes is plotted in the variables of the relative angular velocities of the averaged zonal flow and transfer of vortices about the system rotation axis.
- We demonstrate the generation of a large-scale vortex under the action of small-scale perturbations of the velocity field formed by the interaction of external magnetic fields and radial electric current in thin layer of conducting fluid.
- The formation of large-scale structures under the action of small-scale turbulence can lead to a modification of the general circulation and emerging of a planetary scale vortex with sustained of differential rotation.
- Narrow jet flows that envelop small-scale vortices with cyclonic and anticyclonic rotation were obtained.

- The jet changes its size, precesses, the number of small-scale eddies changes. For a slower rotation ($T = 67$ sec, $h = 24$ mm), a certain violation of the cyclone-anticyclone asymmetry is observed, which is well manifested for relatively fast rotations ($T = 39.8$ sec).
- The jet+vortices structures demonstrate the definite sign of helicity. The changes of the mean helicity well correlate with the energy density.
- In general, the jet flows are characterized by considerable temporal variability, as well as similar structures in the Earth's atmosphere.
- It should be noted that the circular vortices and jet flow were generated both in non-rotating and slowly rotating channels, with or without a conical bottom (i.e., with and without a beta effect).

The experimental results show that transitions to modes different from the initial ones are possible for some parameter values.:

- The number of anticyclonic vortices changes during fast rotations.
- For slower rotations, with the same number of anticyclones, their angular position has changed significantly. There were no transitions to new modes for the intermediate periods, and the final patterns of vortex movements practically did not differ from the initial ones. All experiments were carried out when changing the main parameter of generation: for 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 switching to new modes when the parameter determining the external force of action on the liquid during MHD generation and flow generation by the source-sink method is changed for a while.
- Possible cause is the introduction of noise into the initial stationary flow pattern, which creates the possibility of transition to new modes using noise-induced transition mechanisms.
- This mechanism can be an alternative to low-mode scenarios in the multi-mode problem.

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- A.E.Gledzer et al. JETP, V.113(3), 2011, pp. 516
- A.E.Gledzer et al. Izvestiya, Atmospheric and Oceanic Physics, V.49(2), 2013, pp. 187
- A.E.Gledzer et al. JETP Lett., V.97(6), 2013, pp. 316
- A.E.Gledzer et al. Izvestiya, Atmospheric and Oceanic Physics, V.50(2), 2014, pp. 122
- O.G.Chkhetiani et al., JETP Lett. 101(2), 79 (2015)
- A.E.Gledzer et al. Izvestiya, Atmospheric and Oceanic Physics, V.53(6), 2017, p. 579
- A.E.Gledzer et al. Izvestiya, Physics of the Solid Earth, V.54(4), 2018, p. 574
- A.E.Gledzer et al. Fluid Dynamics, V.56(4), 2021, p. 587
- A.E.Gledzer et al. Izvestiya, Atmospheric and Oceanic Physics, V.59(4), 2023, p. 321
- A.E.Gledzer et al. Doklady Earth sciences, Vol. 520(4), 2025, p. 104