Preface

This book has its origins in courses for graduate and undergraduate students at the Moscow Institute of Physics and Technology (MPhTI). It is the result of over forty years of the author's work in the Laboratory of Geophysical Hydrodynamics founded by A.M. Obukhov in the Institute of Atmospheric Physics (IAP) of the Russian Academy of Science. The first four sections (Part I) are devoted to the basic principles and laws of motion of ideal incompressible and compressible fluids. Particular attention is given to the first integrals of the hydrodynamic equations, and in particular, to the Kelvin invariant and its analogs in stratified incompressible and compressible fluids, the Rossby–Obukhov and Ertel invariants.

In Part II, we discuss what geophysical fluid dynamics is with its unusual properties of fluid motion along isobars and with its suppressed vertical velocity component (the Proudman–Taylor theorem). In deriving the quasi-geostrophic equations of motion we used the axiomatic approach to streamline the presentation. Namely, the whole space of inviscid global geophysical flows is in a sense spanned by the four-dimensional Obukhov–Charney basis, which is defined by the conditions of quasi-hydrostatic and quasi-geostrophic equilibria, as well as the Lagrangian invariance of potential temperature and potential vorticity. The problem of filtering fast motions and adaptation of meteorological fields to the above mentioned equilibria is discussed merely by illustrations and physical reasoning. We introduce the concepts of Rossby waves, their resonant interaction, thermal wind, available potential energy, singular Helmholtz and Obukhov vortices, we derive the Kirchhoff equations for such vortices and demonstrate their applications in geophysical setting.

Part III discusses the problem of the barotropic and baroclinic stability of global geophysical flows. It is preceded by a summary of the classical results in the theory of hydrodynamical stability, which is easily generalized to the case of a rotating fluid. When choosing the material I enjoyed a short and very intelligible book *Hydrodynamical stability and atmosphere dynamics* by L.A. Dikii whose line I followed with minor changes in this book. Our exposition is supplemented by the consideration (following E. Lorenz) of oversimplified nonlinear equations of atmospheric dynamics, which illustrate the evolution of motion after the stability loss by the primary flow. We draw the reader's attention to the mechanism of baroclinic instability and its relation to the available potential energy. In my opinion, the best physical interpretation of this complex phenomenon was given by its discoverer Eady, and a modern account of his work is included in that section.

Viscous geophysical flows and the general atmospheric circulation are discussed in Part IV; its content and exposition differ most of all from the traditional approach to these issues. After deriving the Navier–Stokes equations the reader's attention is focused on describing the geophysical boundary layers, namely, the Ekman and Proudman–Stewartson layers, responsible for the dissipation of kinetic energy of global flows. We derive the quasi-geostrophic equation for the transformation of the potential vorticity of a quasi-two-dimensional barotropic atmosphere taking into account the planetary boundary layer. Starting with this equation we study in detail the linear stability of the Kolmogorov zonal flow (with the sine velocity profile) on the infinite f-plane. In this exceptional case the linear stability problem can be solved analytically. This clearly illustrates the crucial role of exterior friction created by the planetary boundary layer for the stability characteristics of global atmospherical flows. The results of solving this problem are formulated in terms of internal and external Reynolds numbers and then extended to flows with arbitrary velocity profiles. These results point to the structural instability of strictly two-dimensional flows with respect to the inclusion of friction. On the other hand, omitting internal friction has practically no effect on the results of quasi-two-dimensional theory. Thus, it becomes apparent that the crucial parameter of the barotropic atmosphere is the Reynolds number defined by the external friction, rather than the usual Reynolds number reaching astronomical values for global motions. Self-similarity with respect to the internal Reynolds number and the relatively low supercritical response of global movements on the exterior Reynolds number is exactly what explains the relatively quiet nature of general atmospheric circulation, which is not captured by the developed large-scale turbulence.

The final Part V treats the general circulation of the atmosphere with the help of its mechanical prototype, the Euler–Poisson equations of motion of a rigid body, generalized to the case of a rotating system. It is worth mentioning yet one more distinctive feature of this course. Based on the concept of a generalized rigid body introduced by Arnold and the concept of a generalized heavy rigid body introduced by the author, we draw the following analogy. On the one hand, one has the hydrodynamical Euler equations of motion of an ideal fluid and the Oberbeck–Boussinesq equations of motion of a heavy fluid, while on the other hand we deal with the Euler equations of a classical gyroscope and the Euler–Poisson equations for motion of a heavy top. As a consequence, such mechanical invariants as the square of angular momentum and projection of angular momentum to the direction of gravity are treated as the Kelvin and Ertel invariants, respectively. The mechanical prototype of general atmospheric circulation, which has the fundamental symmetry properties of the original, is obtained by introducing linear friction, simulating the effect of the planetary boundary layer and the Newton heat sources, which are proportional to temperature deviations from the background. As a result, based upon analytical calculations and numerical integration of few-component dynamical systems, one can view atmospheric action as a heat engine with its Hadley and Rossby fundamental modes, its reverse meridional circulation cell, its characteristic energy cycle, few-component stochastization, and therefore the weather unpredictability for long periods, as well as its transitions from one long-term metastable weather state to another that are not externally motivated.

For better understanding, each chapter is equipped with exercises, hints, and usually solutions. The literature citation in each chapter is minimal and focuses mainly on the widely available publications where the reader can find more details. The references in the text are given only by the author's name and the publication year and listed at the end of the corresponding section. We give more details on difficult-to-find publications, which are not (yet) included in the well-known editions. The book contains both theoretical and experimental results obtained over years in the Laboratory of Geophysical Hydrodynamics of the IAP RAS by A. Batchaev, V.A. Dovzhenko, V.A. Krymov, D.Yu. Manin, and Yu.L. Chernousko.

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