Modeling Atmospheric and Oceanic Flows

Insights from Laboratory Experiments and Numerical Simulations

Thomas von Larcher and Paul D. Williams

Editors

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Geophysical Monograph 205

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This Work is a co-publication between the American Geophysical Union and John Wiley & Sons, Inc.

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Published by John Wiley & Sons, Inc., Hoboken, New Jersey
Published simultaneously in Canada

Library of Congress Cataloging-in-Publication Data is available.

ISBN: 978-1-118-85593-5

Cover image: The main image shows the sunset over St Brides Bay viewed from Broad Haven, Pembrokeshire, Wales on 4 August 2012, as photographed by Paul D. Williams. The inset image shows a rotating fluid surface visualized by optical altimetry. Different colors correspond to different values of the two components of the horizontal gradient of the surface elevation. The flow is induced by a heated disk on a polar beta plane. Baroclinic instability produces multiple meanders and eddies, which are advected by a zonal current that is flowing anti-clockwise and is driven by the sink in the top-right sector of the image. This flow is a laboratory model of flows occurring in the atmospheres of rotating planets such as Earth and Saturn. More details on the experiment are given in Chapter 5. The image was produced at Memorial University of Newfoundland, Canada, by Y. D. Afanasyev and Y. Sui.

Printed in the United States of America

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PREFACE

The flow of fluid in Earth's atmosphere and ocean affects life on global and local scales. The general circulation of the atmosphere transports energy, mass, momentum, and chemical tracers across the entire planet, and the giant currents of the thermohaline circulation and wind-driven circulation perform the same function in the ocean. These established flows are reasonably steady on long time scales. In contrast, short-lived instabilities may develop and result in transient features such as waves, oscillations, turbulence, and eddies. For example, in the atmosphere, small-scale instabilities are able to grow into heavy storms if the conditions are right.

It is therefore of interest to understand atmospheric and oceanic fluid motions on all scales and their interactions across different scales. Unfortunately, due to the complex physical mechanisms at play and the wide range of scales in space and time, research in geophysical fluid dynamics remains a challenging and intriguing task. Despite the great progress that has been made, we are still far from achieving a comprehensive understanding.

As tools for making progress with the above challenge, laboratory experiments are well suited to studying flows in the atmosphere and ocean. The crucial ingredients of rotation, stratification, and large-scale forcing can all be included in laboratory settings. Such experiments offer the possibility of investigating, under controlled and reproducible conditions, many flow phenomena that are observed in nature. Furthermore, immense computational resources are becoming available at low economic cost, enabling laboratory experiments to be simulated numerically in more detail than ever before. The interplay between numerical simulations and laboratory experiments is of increasing importance within the scientific community.

The purpose of this book is to provide a comprehensive survey of some of the laboratory experiments and numerical simulations that are being performed to improve our understanding of atmospheric and oceanic fluid motion.

On the experimental side, new designs of experiments on the laboratory scale are discussed together with developments in instrumentation and data acquisition techniques and the computer-based analysis of experimental data. On the numerical side, we address recent developments in simulation techniques, from model formulation to initialization and forcing. The presentation of results from laboratory experiments and the corresponding numerical models brings the two sides together for mutual benefit.

The book contains five sections. Section I covers baroclinic instability, which plays a prominent role in atmosphere and ocean dynamics. The thermally driven, rotating annulus is the corresponding laboratory setup, having been used for experiments in geophysical fluid dynamics since the 1940s by Dave Fultz, Raymond Hide, and others. Section II covers balanced and unbalanced flows. Sections III and IV cover laboratory experiments and numerical studies devoted to specific atmospheric and oceanic phenomena, respectively. Section V adresses some new achievements in the computer-based analysis of experimental data and some recent developments in experimental methodology and numerical methods.

We hope this book will give the reader a clear picture of the experiments that are being performed in today's laboratories to study atmospheric and oceanic flows together with the corresponding numerical simulations. We further hope that the lessons learnt from the comparisons between laboratory and model will act as a source of inspiration for the next generation of experiments and simulations.

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ACKNOWLEDGMENTS

We gratefully acknowledge support from the staff at the American Geophysical Union (AGU), particularly Colleen Matan for guiding us through the book proposal process and Telicia Collick for assisting with the external peer review of the chapters. We also extend our thanks to Rituparna Bose at John Wiley & Sons, Inc., for smoothly and professionally handling all aspects of the book production process.

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Section IV: Oceanic Flows

Section V: Advances in Methodology

Introduction: Simulations of Natural Flows in the Laboratory and on a Computer

Paul F. Linden

Humans have always been associated with natural flows. The first civilizations began near rivers, and humans developed an early pragmatic view of water flow and the effects of wind. Experiments and calculations in fluid mechanics can be traced back to Archimedes in his work "On floating bodies" around 250 B.C., in which he calculates the position of equilibrium of a solid body floating in a fluid. He is, of course, attributed with the law of buoyancy known as Archimedes principle. The ancient Greeks also elucidated the principle of the syphon and the pump. This work is essentially concerned with fluid statics, and the first attempts to investigate the motion of fluids is attributed to Sextus Julius Frontinus, the inspector of public fountains in Rome, who made extensive measurements of flow in aqueducts and, using conservation-of-volume principles, was able to detect when water was being diverted fraudulently.

Possibly the first laboratory experiment designed to examine a natural flow was by *Marsigli* [1681] who devised a demonstration of the buoyancy-driven flow associated with horizontal density differences in an attempt to explain the undercurrent in the Bosphorus that flows toward the Black Sea [*Gill*, 1982]. This is a remarkable experiment in that it provides an unequivocal demonstration that flow, now known as baroclinic flow with no net transport, is possible even when the free surface is level, so that there is no barotropic (depth-averaged) flow. These buoyancy-driven flows occur almost ubiquitously in the oceans and atmosphere and are an active area of current research.

Another example of the early use of a laboratory experiment is the explanation of the "dead water" phenomenon observed by the Norwegian scientist *Fridtjof Nansen* [1897], who experienced an unexpected drag on his boat during his expedition to reach the North Pole in 1892. The responsible mechanism, the drag associated with interfacial waves on the pycnocline, was studied by *Ekman* [1904] in his Ph.D. thesis and a review of his work and some modern extensions using synthetic schlieren can be found elsewhere [*Mercier et al.*, 2011].

This last reference nicely demonstrates one role of modern laboratory experiments. Although the basic mechanics has been known since Ekman's study, by careful observation of the flow and making quantitative measurements of the wave fields made possible with new image processing techniques, it has been shown that the dead water phenomenon is nonlinear. The coupling of the large-amplitude interfacial and internal waves with significant accelerations of the boat are an intrinsic feature of the energy transmission from the boat to the waves. Although the essential features have been known for over a century, these recent data provide new insights into the physics of the flows and show that the drag on the boat depends on the forms of the waves generated. Experiments like this provide insight and inspiration about the underlying dynamical processes, ideally motivating theory which can subsequently refocus the experiments.

Numerical methods were first devised to solve potential flow problems in the 1930s, and as far as I am aware the first numerical solution of the Navier-Stokes equations, i.e., the first computational fluid dynamics (CFD) calculation, applied to two-dimensional swirling flow, was published by *Fromm* [1963]. Since then there has been enormous growth in computational power, and this has led to developments in both CFD and laboratory experimentation. The reasons for the improvement in CFD are clear. In order to calculate a flow accurately, it is necessary that the discrete forms of the governing equations are a faithful representation of the continuous partial

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Modeling Atmospheric and Oceanic Flows: Insights from Laboratory Experiments and Numerical Simulations,
First Edition. Edited by Thomas von Larcher and Paul D. Williams.

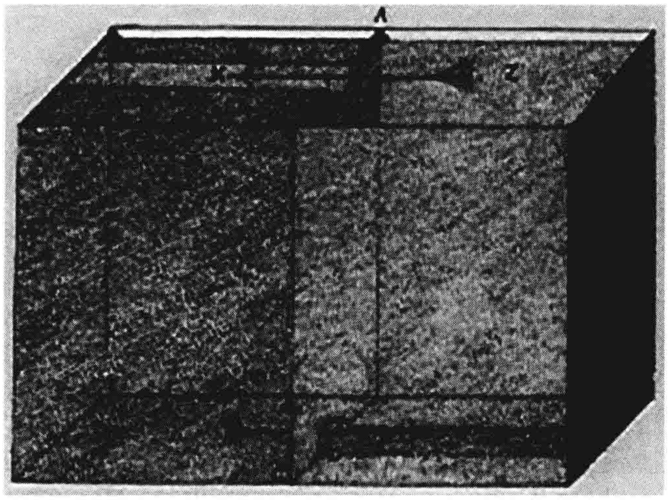

Figure 0.1. A sketch of *Marsigli's* [1681] experiment illustrating the counterflow driven by the density difference between the two fluids in either side of the barrier with flow along the surface toward the denser fluid and a countercurrent along the bottom in the opposite direction.

differential equations. For geophysical flows, which are typically turbulent, this means that in order to avoid approximations it is necessary to compute all the scales of motion, which range from the energy input scales down to the smallest scales, where viscous dissipation occurs. This represents a huge range of scales. Energy is input on global scales (10^6 m) and dissipated at the Kolmogorov scale $(\nu^3/\epsilon)^{1/4} \sim 10^{-3}$ m. This nine decade range of length (and associated time) scales remains well beyond the capabilities of current (and foreseeable) computing power and represents a huge challenge to the computation of geophysical flows.

Geophysical flows are stably stratified (buoyant fluid naturally lies on top of denser fluid) and occur on a rotating planet. The stratification, characterized by the buoyancy frequency N, is of the order of 10^{-2} s^{-1} and is roughly the same in the atmosphere and the oceans. The rotation of Earth is characterized by the Coriolis parameter f, which, with values of order 10^{-4}s^{-1}, introduces longer time scales than those associated with the stratification. Thus, the atmosphere and the oceans, viewed on global scales, are strongly stratified, weakly rotating fluids.

Stratification provides a restoring force to *vertical* motions through the buoyancy force associated with the density difference between the displaced fluid particle and the background stratification. Rotation provides a restoring force due to *horizontal* motions through the Coriolis force (or by conservation of angular momentum viewed in an inertial frame). For motion with horizontal scale L and vertical scale H, the balance between these forces is given by the Burger number B:

$$B \equiv \frac{NH}{fL}. \tag{0.1}$$

Stratification dominates when $B >> 1$, i.e., when horizontal scales are relatively small compared with the Rossby deformation radius $R_D \equiv NH/f$, while rotation dominates when horizontal scales are large compared with R_D and $B << 1$. On global scales the oceans and the atmosphere are thin layers of fluids with vertical to horizontal aspect ratios H/L of order 10^{-3}. Consequently, for motion on global scales in the atmosphere or basin scales in the oceans, $B \sim 10^{-1}$ and rotational effects dominate. These flows can be modeled as essentially unstratified flows, with Coriolis forces providing the main constraints. Motion on smaller scales will generally lead to increasing values of B and increasing effects of stratification. Mesoscale motions, in which buoyancy and Coriolis forces balance, are typified by values of $B \sim 1$, in which case the horizontal scale of the motion is comparable to the Rossby deformation radius R_D, which is on the order of 1000 km in the atmosphere and 100 km in the oceans.

In order to examine the effects of rotation, experiments are conducted on rotating platforms. These are generally high-precision turntables capable of carrying significant weight, and they present a significant engineering challenge in their construction. The requirements and performance of these turntables are discussed in Chapter 7, which illustrates these by considering flows of thin fluid layers in rotating containers of different diameters from 0.1 to 10 m. As the size of the turntable is increased, the engineering requirements become more demanding and the cost increases. Furthermore, larger flow domains require more fluid, and if stratified, this requires a more stratifying agent, such as (the commonly used) sodium chloride. For these reasons most laboratory turntables range up to about 1 m in diameter, and there needs to be a compelling reason to work on large-diameter turntables.

One reason for increasing the experimental scale from 1 to 10 m is to reduce frictional effects. Reynolds numbers $\text{Re} \equiv UL/\nu$, where U and L are typical velocity and length scales and ν is the kinematic viscosity, are increased by a factor of 10 (equivalently Ekman numbers $E \equiv \nu/fL^2$ are reduced by a factor of 100), and so the effects of boundary friction are reduced and damping times are increased at large scale. This can be an dominant factor when studying flows where separation or turbulence is dominant or, as in the case discussed in Chapter 7, the motion of vortices driven by vortex interactions or interactions with topography.

On the other hand, there is little to be gained in terms of the overall Rossby number or Burger number, both of which involve the product fL of rotation and length scale. This product is the speed of the rim of the turntable,