Advances in

GEOPHYSICS

VOLUME 25

Theory of Climate

edings of a Symposium Commemorating the Two-Hundredth
Anniversary of the Academy of Sciences of Lisbon
October 12–14, 1981, Lisbon, Portugal

Edited by

BARRY SALTZMAN

ol. 5

Advances in

GEOPHYSICS

VOLUME 25

Theory of Climate

Proceedings of a Symposium Commemorating the Two-Hundredth Anniversary of the Academy of Sciences of Lisbon
October 12–14, 1981, Lisbon, Portugal

Edited by

BARRY SALTZMAN

Department of Geology and Geophysics
Yale University
New Haven, Connecticut

1983

ACADEMIC PRESS

A Subsidiary of Harcourt Brace Jovanovich, Publishers

New York London
Paris San Diego San Francisco São Paulo Sydney Tokyo Toronto

COPYRIGHT © 1983, BY ACADEMIC PRESS, INC.
ALL RIGHTS RESERVED.
NO PART OF THIS PUBLICATION MAY BE REPRODUCED OR TRANSMITTED IN ANY FORM OR BY ANY MEANS, ELECTRONIC OR MECHANICAL, INCLUDING PHOTOCOPY, RECORDING, OR ANY INFORMATION STORAGE AND RETRIEVAL SYSTEM, WITHOUT PERMISSION IN WRITING FROM THE PUBLISHER.

ACADEMIC PRESS, INC.
111 Fifth Avenue, New York, New York 10003

United Kingdom Edition published by
ACADEMIC PRESS, INC. (LONDON) LTD.
24/28 Oval Road, London NW1 7DX

LIBRARY OF CONGRESS CATALOG CARD NUMBER: 52- 12266

ISBN 0-12-018825-2

PRINTED IN THE UNITED STATES OF AMERICA

83 84 85 86 9 8 7 6 5 4 3 2 1

CONTRIBUTORS

Numbers in parentheses indicate the pages on which the authors' contributions begin.

ROBERT E. DICKINSON, *National Center for Atmospheric Research, Boulder, Colorado 80307* (305)

G. S. GOLITSYN, *Institute of Atmospheric Physics, Academy of Sciences of the USSR, Moscow, USSR* (85)

ARNOLD GRUBER, *Earth Sciences Laboratory, National Earth Satellite Service, NOAA, Washington, D.C. 20233* (237)

SYUKURO MANABE, *Geophysical Fluid Dynamics Laboratory/NOAA, Princeton University, Princeton, New Jersey 08540* (39)

GEORGE OHRING,[1] *Department of Geophysics and Planetary Sciences, Tel-Aviv University, Tel-Aviv, Israel, and National Earth Satellite Service, NOAA, Suitland, Maryland* (237)

ABRAHAM H. OORT, *Geophysical Fluid Dynamics Laboratory/NOAA, Princeton University, Princeton, New Jersey 08540* (355)

JOSÉ P. PEIXÓTO, *Geophysical Institute, University of Lisbon, Lisbon, Portugal* (355)

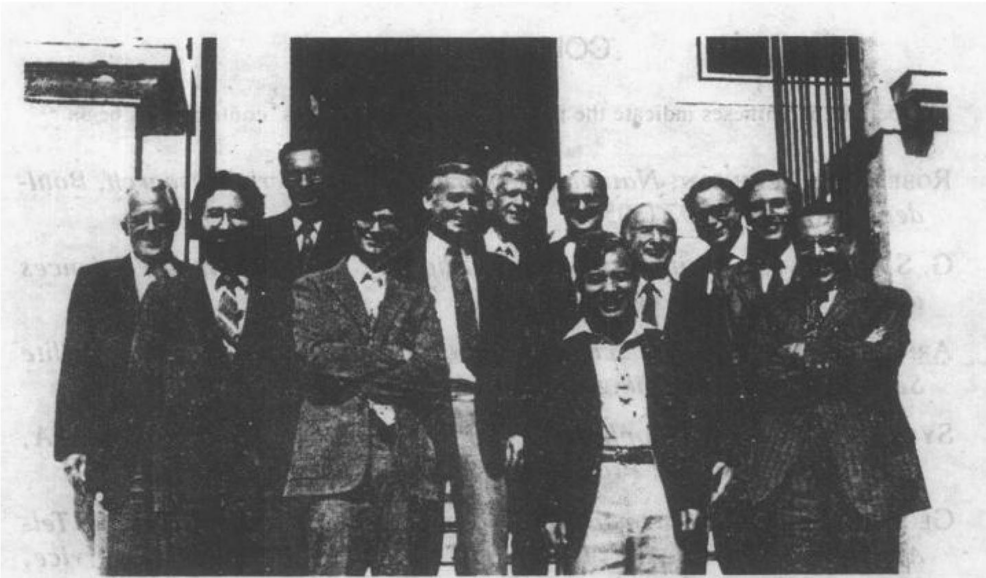
BARRY SALTZMAN, *Department of Geology and Geophysics, Yale University, New Haven, Connecticut 06511* (173)

G. J. SHUTTS,[2] *Atmospheric Physics Group, Department of Physics, Imperial College of Science and Technology, London, United Kingdom* (117)

JOSEPH SMAGORINSKY, *Geophysical Fluid Dynamics Laboratory/NOAA, Princeton University, Princeton, New Jersey 08540* (3)

[1] Present address: Laboratory for Atmospheric Sciences, Climate and Radiation Branch, Code 915, NASA Goddard Space Flight Center, Greenbelt, Maryland 20771.

[2] Present address: Meteorological Office, Bracknell, Berkshire RG12 2SZ, United Kingdom.



Conferees attending the *Symposium on the Theory of Climate*, commemorating the bicentennial of the Academy of Sciences of Lisbon, October 12–14, 1981. From left to right: Erik Eliasen (representing the Danish Academy of Sciences), G. J. Shutts, Barry Saltzman, Robert E. Dickinson, W. Lawrence Gates, George Ohring, Joseph Smagorinsky (rear), Syukuro Manabe (front), Edward N. Lorenz, G. S. Golitsyn, Abraham H. Oort, and José P. Peixoto.

此为试读，需要完整PDF请访问： www.ertongbook.com

FOREWORD

The challenge of achieving a deductive understanding of the long-term behavior of the earth's fluid environment—i.e., a theory of climate—is now recognized to be one of the most important and difficult ever posed, embracing all domains of science. Aside from its purely scientific content, there is a wide awareness of the enormous social ramifications of this subject which universally affects mankind across all national boundaries.

It is altogether fitting, therefore, that in celebration of its two-hundredth anniversary the Academy of Sciences of Lisbon should choose climate theory as the subject for one of the symposia in its commemorative series "Frontiers of Knowledge." We are delighted to be able to present the contributions to this symposium as a special volume of *Advances in Geophysics*.

In all, 10 papers were presented. It was suggested by the conveners that the authors not attempt to review the whole field related to their work, but rather present a more personal account of their "school of thought"—i.e., a synthesis of the body of work that they and their colleagues have produced over a period of time—culminating in some new results. As a whole, the papers conform admirably to this suggestion, representing an excellent mix of much needed review and synthesis with a good deal of new and original material that is testimony to the rapid pace of ongoing work in climate theory.

The papers are divided into three main groups: I. History and Application of General Circulation Models, emphasizing the development and use of large-scale numerical models of the atmosphere to obtain asymptotic equilibrium solutions for the "fast response" parts of the climatic system (Smagorinsky and Manabe); II. Statistical-Dynamical Models, emphasizing simpler, more heavily parameterized models with potential for forming a basis for a time-dependent theory of very long term climatic change involving the slow response parts (Golitsyn, Shutts, and Saltzman); and III. Radiative, Surficial, and Dynamical Properties of the Earth–Atmosphere System, emphasizing observational and diagnostic aspects of global climate (Ohring and Gruber, Dickinson, and Oort and Peixóto). These groups are by no means mutually exclusive; each of the papers contains material overlapping that in other groups. For example, the important role of CO_2 in climate is discussed not only in a major paper by Syukuro Manabe, but also in lesser detail and from other viewpoints in papers by George Ohring and Arnold Gruber, G. S. Golitsyn, and Barry Saltzman.

Only two of the papers delivered at the symposium are not included in this volume. These are the excellent discussions of "The Predictability of the Atmosphere and Its Surroundings" by Edward N. Lorenz and "The Numerical Modeling of Climate" by W. Lawrence Gates. However, both Lorenz and Gates plan to prepare articles covering the material of their talks, with substantial new material, for a forthcoming volume of this serial.

It was with great sadness that the conveners and conferees learned of the death of Jule Charney, whose participation in the symposium had been keenly anticipated. All participants of the symposium agreed that his lifelong work in dynamical meteorology and climate theory provided underpinnings for much that was said at the symposium. Some of Charney's influence on this subject is described in Joseph Smagorinsky's contribution giving a historical account of the beginnings of numerical weather prediction and general circulation modeling.

Speaking as one of the participants in this symposium, and I believe also in behalf of the whole group, I wish to express our special thanks to José Peixóto, President of the Academy of Sciences of Lisbon, who was the driving force behind all the proceedings. These thanks are not only for his major scientific contribution and his introductions and background discussions on all subjects scientific, historical, and cultural, but also for the unsurpassable hospitality he and his associates showed us during our stay in Portugal.

It is the hope of the Publisher that this volume will be a lasting, scientifically significant remembrance of this bicentennial celebration of one of the world's oldest and most renowned scientific institutions, whose insignia we are proud to display as the frontispiece to this volume.

BARRY SALTZMAN

CONTENTS

Parameterization of Traveling Weather Systems in a Simple Model of Large-Scale Atmospheric Flow

G. J. Shutts

Climatic Systems Analysis

Barry Saltzman

Part III. Radiative, Surficial, and Dynamical Properties of the Earth–Atmosphere System

Satellite Radiation Observations and Climate Theory

George Ohring and Arnold Gruber

Land Surface Processes and Climate—Surface Albedos and Energy Balance

ROBERT E. DICKINSON

Global Angular Momentum and Energy Balance Requirements from Observations

ABRAHAM H. OORT AND JOSÉ P. PEIXÓTO

Part I

HISTORY AND APPLICATION OF GENERAL CIRCULATION MODELS

此为试读，需要完整PDF请访问：www.ertongbook.com

THE BEGINNINGS OF NUMERICAL WEATHER PREDICTION AND GENERAL CIRCULATION MODELING: EARLY RECOLLECTIONS

JOSEPH SMAGORINSKY

Geophysical Fluid Dynamics Laboratory/NOAA
Princeton University
Princeton, New Jersey

1. INTRODUCTORY REMARKS

I should say at the outset that my intention here is not to deliver a comprehensive history of the important formative circumstances of the late 1940s and the following decade. The invitation was to make a personal presentation of events in which I had been involved and of which I had first-hand knowledge. I have tried to assemble, from memory and from personal documents, my impressions of the time. My account will therefore be quite selective, but I hope it will be viewed as a useful, if not insightful, contribution to the history by a witness and participant. I therefore apologize in advance for the many lapses in completeness which, no doubt, will be detected by the many others who had been involved in that fascinating period.

The appropriateness of including the era of numerical weather prediction in a symposium on "Advances in the Theory of Climate" is, in retrospect, quite obvious. It was the development of the scientific base and technical methodology needed for the modeling for prediction that paved the way later on for modeling the processes responsible for the general circulation and thereafter for the simulation of climate. In turn, it was the general circulation models that provided the vehicle in the 1960s and 1970s for extending numerical weather prediction beyond a few days.

Hardly any of the events and circumstances touched upon in this account could have happened without Jule Charney. They might have occurred eventually and probably in some other form, but Charney's genius

ADVANCES IN GEOPHYSICS, VOLUME 25

Copyright © 1983 by Academic Press, Inc.
All rights of reproduction in any form reserved.
ISBN 0-12-018825-2

and driving force were singularly responsible for their happening when and how they did. Charney passed from our midst in June 1981. It is my honor to dedicate this work to his memory.

2. Some Personal Antecedents

My interest in meteorology began in my midteens (in the late 1930s) when I thought that weather prediction was somehow accomplished deterministically by the application of physical principles. Quite consistently, I also thought this was true for the design of ship hulls, and in fact at that time my first interest was in naval architecture. But financial and family considerations dominated my career decision, and I entered a university course of study in meteorology. I, of course, quickly learned that my basic assumption was quite incorrect. Weather forecasting was quite subjective, but based on powerful conceptual procedures—the construction of the isobaric weather map and an identification of the air mass and frontal systems. The predicted time–space evolution of the synoptic map was based on the experience of having observed and classified many such evolutions. The forecast of wind, temperature, and precipitation was based on empirical models of how these meteorological parameters would be associated with the predicted pressure field and its attendant air mass and frontal systems.

World War II interrupted my formal university education and I entered a military meteorology training course at the Massachusetts Institute of Technology (MIT) where, in 1943, I came into contact with the eminent dynamic meteorologist, Professor Bernhard Haurwitz. When I asked him why physical principles had not been applied to the practical problem of weather prediction, he quickly pointed out the futility of using the tendency equation to predict surface pressure changes. The actual winds were not sufficiently accurate and the geostrophic approximation would give nonsensical measures of the horizontal divergence. When queried further, Haurwitz did recall the work of L. F. Richardson during and just after World War I, but, as I remember, did not attach great importance to its implications.

I was resigned to frustration and disappointment which remained dormant until the end of the decade. I returned to civilian life, resumed my university education, and went on to complete a master's degree with emphasis on dynamic meteorology. My first position was as a research meteorologist at the U.S. Weather Bureau under Dr. Harry Wexler. In 1949, I heard a lecture by Jule Charney which changed my life. His systematic analysis of the scale properties of large-scale atmospheric motions and his presentation of a rational approach to deriving a geostrophically consistent set of prediction equations, reawakened my hopes for a hydrodynamic framework for prediction. I did not, of course, know how far Charney's ideas would carry in shaping, and indeed revolutionizing, the physical and dynamical basis for weather prediction. In fact, we now know that the basic methodology would eventually find its way into the study of a much broader part of the spectrum of phenomena than midtropospheric Rossby waves. With the modern high-speed electronic computer, then under development by von Neumann and his colleagues at the Institute for Advanced Study in Princeton, it would eventually be possible to study synoptic-scale baroclinic processes, the dynamics of convection and mesoscale phenomena, the general circulation, climate, and even the ocean circulation.

In one day, my visions were completely transformed. Little did I know that I would be privileged to participate in a scientific revolution that, when I first made my career choice, I had mistakenly thought had already happened at the time.

3. The Institute for Advanced Study 1949–1953

The formation of the Meteorology Group at the Institute for Advanced Study (IAS) in Princeton and its first numerical forecasts on the Electronic Numerical Integrator and Computer (ENIAC) were key events in the early history of numerical weather prediction. These events were eloquently described in authoritative detail in a lecture[1] in memory of Professor Victor P. Starr at MIT in 1979 by Professor George W. Platzman, who himself was instrumental during that period. Here, I will only try to supplement his account with additional documented contemporary impressions, keeping duplication at a minimum. At this point one should note that remarkably parallel developments were taking place in the Soviet Union during the 1940s and 1950s. But because scientific communications with the West did not begin to fully develop until the late 1950s, much of the Soviet work was largely unknown until an excellent comparative survey of research through 1959 was published by Phillips, Blumen, and Coté in 1960.[2]

Based on John von Neumann's radically new logical ideas for a stored program computer using Williams's cathode ray tube technology as a

[1] Platzman, G. W. The ENIAC computations of 1950—gateway to numerical weather prediction. *Bull. Am. Meteorol. Soc.* **60**(4), 302–312 (1970).

[2] Phillips, N. A., Blumen, W., and Coté, O. Numerical weather prediction in the Soviet Union. *Bull. Am. Meteorol. Soc.* **41**(11), 599–617 (1960).

storage device, an Electronic Computer Project was established in 1946 at the IAS. Only von Neumann's great reputation and persuasive power were able to overcome the opposition of the faculty to so mundane an enterprise. The circumstances surrounding this event are well documented in a book by H. H. Goldstine,[3] who was one of the prime movers on the project. As he points out, a threefold thrust was intended: engineering, numerical mathematics, and some important and large-scale applications. For the latter, von Neumann selected numerical meteorology. This was based on his knowledge of Richardson's earlier work and also on encouragement by Carl-Gustav Rossby of the University of Chicago and Harry Wexler of the U.S. Weather Bureau. It was recorded at the time:[4]

> A project whose ultimate effects on weather forecasting may be revolutionary has been quietly under way during the past year in the academic surroundings of the Institute for Advanced Study, Princeton, New Jersey. . . . In August 1946, a conference of meteorologists met in Princeton to discuss the project. . . . Since last summer, work has gone forward in promising fashion, though it is still far too early to expect immediate, tangible results. . . . The immediate aims of this group are the selection and mathematical formulation of meteorological problems to be solved by the electronic computer . . . the most interesting feature of the project is the effort being made to link the theory behind atmospheric processes with future weather.

After failing to persuade Rossby to come to the Institute to lead the effort, von Neumann invited one of Rossby's young proteges from the University of Chicago, Albert Cahn, Jr., who was then succeeded by Philip D. Thompson.

Charney, who had been a graduate student of J. Holmboe's at the University of California at Los Angeles, came to Rossby's attention when he briefly served as a research associate at the University of Chicago in 1946–1947 on his way to a postdoctoral appointment at the University of Oslo. During that academic year, Rossby, with a distinguished group of collaborators, produced a famous synoptic, theoretical, and experimental paper on the interaction of long waves with the zonal circulation.[5] Although Charney was at Chicago for only part of the duration of that project, he impressed Rossby to the point where Charney was invited to lead the IAS Meteorology Group upon his return from Oslo in 1948. It was in Oslo that he wrote his scale paper.[6]

Charney immediately invited Arnt Eliassen to join him. Eliassen had by

[3] Goldstine, H. H. "The Computer from Pascal to von Neumann." Princeton Univ. Press, Princeton, New Jersey, 1972.

[4] "Electronic Computer Project," Weather Bureau Topics and Personnel, July 1947.

[5] Staff Members of the Department of Meteorology of the University of Chicago (J. G. Charney, G. P. Cressman, D. Fultz, L. Hess, A. D. Nyberg, E. V. Palmen, H. Riehl, C. G. Rossby, Z. Sekera, V. P. Starr, and T.-C. Yeh). On the general circulation of the atmosphere in middle latitudes. *Bull. Am. Meteorol. Soc.* **28**, 255–280 (1947).

[6] Charney, J. G. On the scale of atmospheric motions. *Geofys. Publ.* **17**(2), 1–17 (1948).

that time completed his definitive paper on a consistent formulation of the hydrostatically conditioned equations in pressure coordinates.[7] That was the beginning of the famous Meteorology Group. Charney was also joined by a young mathematician, Gilbert A. Hunt. It was this triumvirate that, in January 1949, reported on a "Program for Numerical Weather Prediction" in New York that had captivated me. Hunt, soon after, returned to his first love and is now a distinguished Professor of Mathematics at Princeton University.

The beginning of the collaboration of Charney and Eliassen in Oslo produced two key papers after they reunited in Princeton. The first, by Charney himself,[8] was a comprehensive rationale which laid the foundation for dynamical prediction. It justified the use of the geostrophic approximation to filter small-scale high-frequency noise from the vorticity equation, discussed the propagation of signal and its implications on data requirements, introduced the notion of the equivalent-barotropic atmosphere to reduce the forecast problem to a two-dimensional one, and finally, showed how Green's functions could be used to make a linear one-dimensional prediction for an arbitrary initial geopotential distribution at midtroposphere. A companion paper, submitted a few days later by Charney together with Eliassen,[9] gave the results of one-dimensional predictions (along a latitude band) and also applied these techniques to the study of topographically produced quasi-stationary perturbations.

In those early days, Charney's group for the most part consisted of two to four meteorologists on visits for about one year. The main exception was Norman A. Phillips, who arrived in 1951 after completing his Ph.D. at the University of Chicago and moved to MIT with Charney in 1956.

In 1949, I was invited as an occasional visitor, from my base in Washington, D.C., to assist the group in extending its one-dimensional linear barotropic calculations. On behalf of the Weather Bureau, I also was asked to become familiar with the theoretical aspects of a more realistic model. As a result of a month-long visit in the spring of 1949, I recorded in a report:[10]

> Essentially, the new method is a much refined form of the vorticity theorem enunciated by Rossby in the late 1930's. Although this model is, as Rossby's, a barotropic fluid in one-dimensional motion which only considers small perturbations, it can take into account [equivalent-barotropic] divergence, the mean finite lateral width of a disturbance, friction, topography, an arbitrary initial pressure disturbance, and the

[7] Eliassen, A. The quasi-static equations of motion with pressure as independent variable. *Geofys. Publ.* **17**(3), 1–44 (1949).

[8] Charney, J. G. On a physical basis for numerical prediction of large-scale motions in the atmosphere. *J. Meteorol.* **6**, 371–385 (1949).

[9] Charney, J. G., and Eliassen, A. A numerical method for predicting the perturbations of the middle latitude westerlies. *Tellus* **1**(2), 38–54 (1949).

[10] Memorandum, Smagorinsky to Chief of Bureau [F. W. Reichelderfer], June 30, 1949.

此为试读，需要完整PDF请访问：www.ertongbook.com