The Stratosphere: Dynamics, Transport, and Chemistry

L. M. Polvani, A. H. Sobel, and D. W. Waugh
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Geophysical Monograph 190

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Editors

American Geophysical Union
Washington, DC

Published under the aegis of the AGU Books Board

Kenneth R. Minschwaner, Chair; Gray E. Bebout, Joseph E. Borovsky, Kenneth H. Brink, Ralf R. Haese, Robert B. Jackson, W. Berry Lyons, Thomas Nicholson, Andrew Nyblade, Nancy N. Rabalais, A. Surjalal Sharma, and Darrell Strobel, members.

Library of Congress Cataloging-in-Publication Data
The stratosphere : dynamics, transport, and chemistry / L.M. Polvani, A.H. Sobel, D.W. Waugh, editors.
p. cm. — (Geophysical monograph series ; 190)
Includes bibliographical references and index.
ISBN 978-0-87590-479-5 (alk. paper)
1. Stratosphere. 2. Whirlwinds. 3. Dynamic meteorology. I. Polvani, L. M. (Lorenzo M.), 1961- II. Sobel, Adam H., 1967- III. Waugh, D. W. (Darryn W.)
QC881.2.S8S875 2010
551.51'42—dc22
2010043355

ISBN: 978-0-87590-479-5
ISSN: 0065-8448

Cover Image: A stupendous show of nacreous clouds photographed in September 2003 at McMurdo Station, Antarctica. These iridescent clouds, also known as “polar stratospheric clouds,” are observed in the lower stratosphere during spring and play a crucial role in the formation of the ozone hole. Photo courtesy of Seth White.

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Printed in the United States of America.

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FOREWORD:
R. Alan Plumb—A Brief Biographical Sketch and Personal Tribute

Adam H. Sobel

Department of Applied Physics and Applied Mathematics and Department of Earth and Environmental Sciences, Columbia University
New York, New York, USA
Lamont-Doherty Earth Observatory, Earth Institute at Columbia University, Palisades, New York, USA

Raymond Alan Plumb was born on 30 March 1948 in Ripon, Yorkshire, United Kingdom. He is not known for talking about his childhood, but we do know that he liked to sing and was part of a group called the Avocets.

Alan did his undergraduate degree in Manchester, obtaining his BS Physics with I Honors in 1969. He was offered a fellowship to do his PhD at Cambridge, but he had a negative reaction to a visit there and decided to stay at Manchester, where he pursued his studies in Astronomy, completing his PhD in 1972. With a highly disengaged thesis advisor, Alan was largely self-taught as a graduate student. He studied planetary atmospheres. Toward the end of his studies, Alan participated in a summer school organized by Steve Thorpe in Bangor, Wales, where he came into contact with the broader international community in geophysical fluid dynamics. Raymond Hide became particularly influential and became Alan's mentor at the UK Meteorological Office (UKMO), where Alan worked for 4 years after receiving his PhD. Another key early influence whom Alan met then was Michael McIntyre. McIntyre's interest and encouragement were very important to Alan at that early time and would continue to be so in later years, including after his move to Australia.

Alan's first peer-reviewed journal article, "Momentum transport by the thermal tide in the stratosphere of Venus" [*Plumb*, 1975] was based on his PhD thesis, though it came out several years after his degree. This first paper shows that even at this early point in his career Alan was a mature scientist, with an approach that has since remained remarkably constant. The young Dr. Plumb was already an expert practitioner of what we now know as classic geophysical fluid dynamics. His mathematics is elegant and sophisticated but never more complex than necessary and is combined with great physical insight and clarity of exposition. Certain themes from this and his other earliest papers have stayed at the forefront of his work to the present: angular momentum; wave-mean flow interaction; and the interplay of conservative and nonconservative processes (advective and diffusive transport and sources and sinks of tracers). Above all, one finds in these early papers an author seeking the most direct route from fundamental physical laws to observed behavior.

Alan's first position at the UKMO was Scientific Officer, then Senior Scientific Officer. As a member of Hide's group, Alan had great freedom to pursue his interests in fundamental geophysical fluid dynamics (GFD). UKMO policy at that time, however, commonly required anyone in Alan's position to switch groups after 3 years or so. In Alan's case, any other group he might have joined likely would have given him greater operational responsibilities, taking him away from basic research. Largely in response to this, Alan moved in 1976 to the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Aspendale, a suburb of Melbourne, Australia.

CSIRO was at that time hospitable to basic, curiosity-driven research. It was very strong in dynamical and physical meteorology with a roster of young scientists whose names are now familiar to many in our field (e.g., Webster, Stephens, Frederiksen, and Baines). Alan's contributions in stratospheric dynamics drew international attention and were proudly touted by the lab in annual reports at the time.

Alan's papers from the early CSIRO years cover a mix of explicitly middle-atmospheric topics (quasi-biennial oscillation (QBO), equatorial waves, meridional circulations, sudden warmings, and mesospheric 2 day waves) with theoretical

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10.1029/2010GM000998

GFD papers whose applicability was broader, though they may have been motivated by stratospheric problems. One of my favorites in the latter category is *Plumb* [1979]. In this paper, Alan shows that transport of a scalar by small-amplitude waves is diffusive in character if either the scalar is subject to damping (such as Newtonian cooling in the case of temperature, or in the case of a chemical species, reactions that can be represented as relaxation toward a chemical equilibrium state) or the waves are growing in time. At the same time, it also showed that the eddy fluxes often do not appear diffusive because when the waves are almost steady and conservative, the fluxes are dominated by the off-diagonal (i.e., advective) components of the diffusion tensor wherever the Stokes drift is nonzero, as it usually is. That was not realized at the time, and it showed how important it is to use the residual, not the Eulerian mean, velocity as the advecting velocity when trying to parameterize eddy transport. Though not one of Alan's most cited papers (as of this writing, it is ranked sixteenth, with 93 citations), this one is a contribution of the most fundamental sort. Diffusion, in the sense of Fick or Fourier (in which the local time tendency of some scalar field is proportional to its Laplacian in space), is by far the simplest and best understood transport process. It is of great value to know when nominally more complex processes lead to diffusive behavior. A. Einstein showed that Brownian motion leads to diffusive transport when viewed statistically on large scales, and G. I. Taylor showed that fluid turbulence, under some circumstances, does as well. Linear waves and turbulence are entirely different sorts of fluid flows, so Alan's explanation of the diffusive as well as advective character of linear waves deserves, in my view, to be mentioned in the same sentence as Einstein's and Taylor's papers in any historical discussion of tracer transport in fluids.

Another favorite of mine is *Plumb* [1986] in which Alan generalizes the quasi-geostrophic Eliassen-Palm flux to three dimensions. This was a great demonstration of technical mastery, but more importantly, a work of fundamental significance, building the basic toolbox our field needs to understand cause and effect in the atmosphere. Few scientists are able both to recognize when problems like this need to be solved and to solve them.

One of Alan's more dramatic achievements at CSIRO was the tank experiment demonstrating in the laboratory the mechanism for the quasi-biennial oscillation [*Plumb and McEwan*, 1978]. Figure 1 [from *Garratt et al.*, 1998] shows Alan explaining this experiment to a group of visitors to CSIRO. *Lindzen and Holton* [1968] had proposed that upward propagating gravity waves, with time scales of days or

Figure 1. Alan Plumb shows his QBO water tank experiment to Bill Priestley and other dignitaries at CSIRO [from *Garratt et al.*, 1998]. © Copyright CSIRO Australia.

less, interacted systematically with the mean flow to generate an oscillation in the stratospheric winds with a period of over 2 years. The mechanism was inherently multiscale and nonlinear, with the amplitude of the waves determining the frequency of the QBO. While this idea must have seemed exotic at the time, its essential elements were familiar to Alan from his thesis work on wave-mean flow interaction in the Venusian atmosphere. Characteristic of Alan's later work both in research and education, his essential contribution was not only in understanding the physics better than most others (as demonstrated by several classic papers from the early CSIRO period [*Plumb*, 1977; *Plumb and Bell*, 1982a, 1982b] in which Alan fleshed out the skeleton of the Holton-Lindzen theory, painting a physical picture of the QBO in three dimensions that in many respects stands unchanged today) but in recognizing what made it difficult for others to understand and how to make it easier for them.

Alan's colleagues from the CSIRO period describe him as one of the leading lights of the field in Australia at the time and as an unselfish collaborator. Robert Vincent, of Adelaide University, recounted to me regular trips Alan made to Adelaide, a relative backwater compared to Melbourne. Alan brought with him all the latest theoretical developments, but he was also profoundly interested in and knowledgeable about observations. With Vincent's group, Alan played an instrumental role in developing a technique to estimate mesospheric eddy momentum fluxes from radar measurements. Robert Bell (CSIRO) was employed as a computer programmer working with different investigators and wrote the code used to obtain the results detailed by *Plumb and Bell* [1982a, 1982b]; Bell recounted the pleasure and satisfaction of working with Alan on this project and also how it helped to establish his (Bell's) career, bringing him recognition and subsequent collaborations with other scientists.

Alan's colleagues from his Australian period also describe him with much fondness as a good friend with an active social life. He served as stage manager for a local musical theater company (though he claims that he did not sing any roles), played volleyball, and brewed a strong beer. In hearing these recollections and others, one gets hints of certain nonscientific anecdotes whose existence is acknowledged, but whose details are not divulged, at least not to Alan's students (i.e., me). It seems that Alan's reputation as the most reserved of Englishmen has been earned partly through occasional departures from that role, though the details are likely to remain unknown to those who were not near him in Melbourne at that time.

Later in Alan's time at CSIRO, during the mid and late 1980s, his scientific interests evolved toward transport problems of more direct relevance to stratospheric chemistry, more direct interaction with the comprehensive numerical models of the time, and more collaboration with American scientists. The latter may have been in part a consequence of an extended visit to NOAA's Geophysical Fluid Dynamics Laboratory in 1982.

After 1985, the discovery of the ozone hole drove excitement and growth in the study of the stratosphere. Despite the ozone hole's location in the Southern Hemisphere, much of the activity was in the United States, where F. Sherwood Rowland and Mario Molina had made the original predictions of ozone loss due to chlorofluorocarbons (CFCs). In the late 1980s, NASA began a series of aircraft experiments to better assess the chemistry and transport of ozone and the key species influencing it. Alan would play an important role in these experiments after his move to the United States in 1988, and perhaps this move was partly motivated by a desire to be closer to the center of things.

Also, however, CSIRO was changing to favor more applied work funded by short-term contracts, which made it more difficult for Alan (and other basic researchers, many of whom left around this time) to pursue his interests. Alan's international reputation earned him an offer of a faculty position at the Massachusetts Institute of Technology (MIT) in the great department that had been home to Jule Charney, Ed Lorenz, Victor Starr, and others and still was arguably the leading department in GFD. In 1988, Alan moved to the United States for reasons similar to those which had brought him to Australia: at MIT he could better pursue his interest in the basic physics controlling the circulation of the Earth's atmosphere.

At MIT, Alan's interests continued to broaden. One new direction, motivated by his participation in the NASA aircraft experiments, was in nonlinear polar vortex dynamics and transport. With Darryn Waugh, Alan used the contour advection with surgery approach to diagnosing (and even forecasting during field experiments) the generation of fine-scale filaments of polar vortex air in the midlatitude surf zone due to Rossby wave breaking events [*Waugh and Plumb*, 1994; *Waugh et al.*, 1994; *Plumb et al.*, 1994]. The discovery that the formation of such fine-scale features could be accurately predicted using only low-resolution meteorological data was a remarkable breakthrough that spawned a huge number of follow-on studies, theoretical and applied, by many other researchers.

Another new thread in Alan's portfolio was tropical tropospheric dynamics, particularly the dynamics of the Hadley circulation and monsoons [*Plumb and Hou*, 1992; *Hsu and Plumb*, 2000; *Plumb*, 2007b; *Privé and Plumb*, 2007a, 2007b; *Clift and Plumb*, 2008]. At first glance, this topic may seem disconnected from Alan's work on the stratosphere. Once one recognizes the central role played by angular momentum in this work, the connection is clear; one of the central results in the now classical axisymmetric theory developed by Edwin Schneider and Richard Lindzen [*Schneider and Lindzen*, 1977; *Schneider*, 1977], Isaac Held and Arthur Hou [*Held and Hou*, 1980], and then Alan is known as Hide's theorem, due to Alan's former mentor.

Perhaps the most broadly influential of all the work from Alan's first decade at MIT is a remarkable series of papers that grew out of Alan's study of tracer-tracer correlations in aircraft data. The series really begins with *Plumb and McConalogue* [1988], but the central ideas were established in the mind of the community by *Plumb and Ko* [1992]. This study clarified the conditions under which compact relations between simultaneous measurements of different tracers would be expected and the further conditions under which those relations would be linear, and it generally clarified the roles of transport and chemistry in creating or breaking these compact relations. It continues with *Hall and Plumb* [1994], which clearly defined the concept of age of air, continues further with *Plumb* [1996], which broadened the theory of *Plumb and Ko* [1992] to include an isolated tropics, or tropical pipe, and then has continued since with further developments [*Waugh et al*., 1997; *Neu and Plumb*, 1999; *Plumb*, 2007a].

It is difficult to overstate the impact this work had on the field at the time. I had the good fortune to be Alan's student during this period, and he gave me the opportunity to attend a number of conferences and workshops. The roughly decade-long wave of excitement and rapid progress (and funding) in stratospheric chemistry and transport that followed the discovery of the ozone hole had not yet passed, and avalanches of results from new field experiments, satellite measurements, and numerical models of stratospheric trace gases were still pouring in at these meetings. Alan was unquestionably the most important theorist in this scene. He cast a long shadow over each meeting, even if he was not there and even though he didn't say much (apart from his own presentations) when he was. As soon as each new Plumb paper became available (often before publication), other scientists from many institutions would scramble to reorient their research, doing their best to make use of Alan's new insights or to use their own tools to try to address the new questions Alan's new conceptual framework raised.

In more recent years, Alan's work has evolved in new directions again. One of these is stratosphere-troposphere interaction, where Alan has turned his attention to the physics of annular modes and the mechanisms by which stratospheric dynamics may influence tropospheric weather. Another is physical oceanography. Here many of the ideas that evolved through the work of Alan and others in the context of the stratosphere are relevant, directly or indirectly, to the ocean; the ocean is, as is often said, more like the stratosphere than it is like the troposphere, because of the relative weakness of vertical mixing processes and internal heating and resulting strong control exerted by stratification.

Since his move to MIT, Alan has been an educator as well as a research scientist. His record as a teacher and mentor is perhaps less widely known than his research record, but it is no less stellar. Here I can speak from my own personal experience as well as that of all the other alumni I have come to know who worked with Alan or took his courses before, during, and after my time as Alan's student at MIT.

Alan's classroom courses are models of clarity. The experience of taking one of them is basically a semester-long, much more in-depth version of the experience of reading one of Alan's journal articles. One feels that one has been taken from a point of ignorance to a point of deep understanding by the shortest route. This is a very rare experience, not at all common to all classroom teachers, even those few whose research records are comparable to Alan's. His lecture notes on middle atmosphere dynamics are, in my view, better than any textbook on the subject, though it is the field's loss that he has never published them. He has, more recently, coauthored with John Marshall an outstanding textbook [*Marshall and Plumb*, 2008] based on their undergraduate course.

As a mentor (speaking again from my own experience), Alan was hands-off while still providing critical insightful guidance. Owing to the many demands on Alan's time, I could not necessarily get to see him very frequently or on short notice. When I did, the dynamic range of his reactions to the results I showed him was narrow; it took me a year or two to learn that a furrowed brow and mildly perplexed look was a pretty negative reaction even if not accompanied by any harsh words, while the phrase "that's good" was the highest praise. Once I understood that, Alan was the best of mentors. If I was doing well, he let me go my own way, allowing me to develop as a scientist without micromanagement. If I started to drift in an unproductive direction, I was redirected in a way that left me feeling wiser rather than chastised. In a discussion with Alan, no words were wasted, at least none of his. Whatever the source of my confusion, Alan grasped it quickly and saw how to move me past it.

Alan's former graduate students, postdocs, and junior collaborators on whom his influence has been formative have gone on to positions of prominence at a wide range of scientific institutions around the world; on the faculty of Columbia University alone, where the PlumbFest was held, three of us (Lorenzo Polvani, Tim Hall, and myself) consider ourselves Alan's proteges.

Alan is famous among all who have encountered him, either at MIT or in the broader scientific sphere, for the kind respect with which he treats everyone. Alan never makes one feel stupid, even when one is. This trait stands out because it is far from universal among scientists of Alan's caliber (or even much lesser ones).

At the present time, Alan continues down the path he has been on since the start of his career in Manchester: finding elegant solutions to difficult and important scientific problems and explaining them in the most effective and clear way to students and colleagues. On the occasion of his 60th birthday, some of us gathered in New York City to mark the occasion and to discuss the science of the stratosphere, to which he has contributed so much. On behalf of those of us who were present there, and those who were not but shared our feelings, I wish Alan health, happiness, and many more years in which to keep doing what he does.

Acknowledgments. Conversations with a number of people informed this piece, though I take responsibility for any errors. I thank Robert Bell, Paul Fraser, Jorgen Frederiksen, Harry Hendon, Michael McIntyre, and Robert Vincent, as well as, of course, Alan himself, for discussions and insight into R. Alan Plumb's career. Darryn Waugh provided useful feedback on the first draft.

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PREFACE

The year 2008 marked the 60th birthday of R. Alan Plumb, one of the great atmospheric scientists of our time. To celebrate this anniversary, a symposium was held at Columbia University on Friday and Saturday, 24–25 October 2008: this event was referred to, affectionately, with the nickname PlumbFest. A dozen invited speakers gave detailed presentations, reviewing the recent advances and the current understanding of the dynamics, transport, and chemistry of the stratosphere. In order to make the PlumbFest an event of lasting significance, it was decided to invite the symposium speakers to write chapter-length review articles, summarizing our present knowledge of the stratosphere: hence the present Festschrift volume. With heartfelt gratitude, it is dedicated to our mentor, colleague, and friend, Alan Plumb, *il miglior fabbro*!

Lorenzo M. Polvani
Columbia University

Adam H. Sobel
Columbia University

Darryn W. Waugh
Johns Hopkins University

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10.1029/2010GM001019

Introduction

Darryn W. Waugh

Department of Earth and Planetary Sciences, Johns Hopkins University, Baltimore, Maryland, USA

Lorenzo M. Polvani

Department of Applied Physics and Applied Mathematics and Department of Earth and Environmental Sciences
Columbia University, New York, New York, USA

Over the past few decades there has been intensive research into the Earth's stratosphere, which has resulted in major advances in our understanding of its dynamics, transport, and chemistry and its coupling with other parts of the atmosphere. This interest in the stratosphere was originally motivated by concerns regarding the stratospheric ozone layer, which plays a crucial role in shielding Earth's surface from harmful ultraviolet light. In the 1980s the depletion of ozone was first observed, with the Antarctic ozone hole being the most dramatic example, and then linked to increases in chlorofluorocarbons (CFCs). These findings led to the signing of the Montreal Protocol, which regulates the production of CFCs and other ozone-depleting substances. Over the subsequent decades, extensive research has led to a much better understanding of the controls on stratospheric ozone and the impact of changes in CFC abundance (including the recovery of the ozone layer as the abundance of CFCs returns to historical levels). More recently, there has been added interest in the stratosphere because of its potential impact on surface climate and weather. This surface impact involves changes in the radiative forcing, the flux of ozone and other trace constituents into the troposphere, and dynamical coupling.

The aim of this monograph is to summarize the last two decades of research in stratospheric dynamics, transport, and chemistry and to provide a concise yet comprehensive overview of the state of the field. By reviewing the recent advances this monograph will act, we hope, as a companion to the *Middle Atmosphere Dynamics* textbook by *Andrews et al.* [1987]. This is the most widely used book on the stratosphere and provides a comprehensive treatment of the fundamental dynamics of the stratosphere. However, it was published over 20 years ago, and major advances in our understanding of the stratosphere, on very many fronts, have occurred during this period. These advances are described as in this monograph.

The chapters in this monograph cover the dynamical, transport, chemical, and radiative processes occurring within the stratosphere and the coupling and feedback between these processes. The chapters also describe the structure and variability (including long-term changes) in the stratosphere and the role played by different processes. Recent advances in our understanding of the above issues have come from a combination of increased observations and the development of more sophisticated theories and models. This is reflected in the chapters, which each include discussions of observations, theory, and models.

The first chapter [*Geller*, this volume] provides a historical perspective for the material reviewed in the following chapters. It describes the status of research and understanding of stratospheric dynamics and transport before Alan Plumb's entrance into stratospheric research.

The second chapter (by Alan Plumb himself [*Plumb*, this volume]) describes recent developments in the dynamics of planetary-scale waves, which dominate the dynamics of the winter stratosphere and play a key role in stratosphere-

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10.1029/2010GM001018

troposphere couplings. While there is a long history in understanding the propagation of these waves in the stratosphere, some very basic questions remain unsolved, the most important being the relationship between planetary-scale Rossby wave activity and the mean flow, which are discussed in chapter 2.

The chapter by *Waugh and Polvani* [this volume] covers the dynamics of stratospheric polar vortices. The observed climatological structure and variability of the vortices are reviewed, from both zonal mean and potential vorticity perspectives, and then interpreted in terms of dynamical theories for Rossby wave propagation and breaking. The role of vortices in troposphere-stratosphere coupling and possible impact of climate change of vortex dynamics are also discussed.

Kushner [this volume] provides a review of the so called “annular modes,” which are the principal modes of variability of the extratropical circulation of the troposphere and stratosphere on time scales greater than a few weeks. The observed characteristics of these annular modes in each hemisphere are presented, together with a discussion of their dynamics and their role in extratropical climate variability and change.

Gray [this volume] focuses on the dynamics of the equatorial stratosphere. The characteristics of the quasi-biennial oscillation (QBO) and semiannual oscillation (SAO), which dominate the variability in zonal winds and temperatures near the equator, are summarized. The interaction of thee QBO and the SAO with the solar cycle and their impact on the extratropics and the troposphere, as well as on the transport of ozone and other chemical species, are also reviewed.

The chapter by *Alexander* [this volume] focuses on gravity waves in the stratosphere. Recent research on the direct effects of these waves in the stratosphere, including their effects on the general circulation, equatorial oscillations, and polar ozone chemistry, are highlighted. Advances in our understanding of the sources of gravity waves and in parameterizing these waves in global models are also discussed.

Randel [this volume] describes the observed interannual variability and recent trends in stratospheric temperature and water vapor. There is also a discussion of mechanisms causing these changes, including long-term increases in carbon dioxide, volcanic eruptions, the QBO, and other dynamical variability, as well as an examination of the link between variability in stratospheric water vapor and temperature anomalies near the equatorial tropopause.

Schoeberl and Douglass [this volume] provide an overview of stratospheric circulation and transport as seen through the distribution of trace gases. They also summarize the techniques used to analyze trace gas distributions and transport and the numerical methods used in models of tracer transport.

The chapter by *Newman* [this volume] deals with polar ozone and chemistry, with a focus on the Antarctic ozone hole. The chapter offers an updated overview of observed changes in polar ozone, our current understanding of polar ozone losses, the heterogeneous chemistry behind those loss processes, and a short prognosis of the future of ozone levels.

The final chapter [*Haigh*, this volume] reviews what is known about solar variability and the evidence for solar signals in the stratosphere. It discusses the relevant radiative, chemical, and dynamical processes and to what extent climate models are able to reproduce the observed signals. It also discusses the potential for a solar impact on the stratosphere to influence tropospheric climate through dynamical coupling.

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L. M. Polvani, Department of Applied Physics and Applied Mathematics, Columbia University, New York, NY 10027, USA. (lmp@columbia.edu)

D.W. Waugh, Department of Earth and Planetary Sciences, Johns Hopkins University, Baltimore, MD 21218, USA.

Middle Atmosphere Research Before Alan Plumb

Marvin A. Geller

School of Marine and Atmospheric Science, State University of New York at Stony Brook, Stony Brook, New York, USA

Alan Plumb received his Ph.D. in 1972. Since that time, he has made very great contributions to middle atmosphere research. This paper briefly examines the status of middle atmosphere research upon Alan's arrival on the scene and his development into one of the world's leading researchers in this area.

1. INTRODUCTION

Alan Plumb has been one of the principal contributors to research into middle atmosphere dynamics and transport for over 3 decades now, so it is difficult to imagine the field without his great contributions, but it is good to remember the famous quote from Isaac Newton's 1676 letter to Robert Hooke, "If I have seen a little further it is by standing on the shoulders of Giants." Alan's work similarly built on the work of those that came before him, just as many younger atmospheric scientists make their contributions standing on Alan's shoulders.

Alan has made significant contributions in many areas, but I will concentrate on those aspects of his work that are in the broad areas of wave–mean flow interactions and middle atmosphere transport. The following then is my version of the status of our understanding of these fields in the "before Alan Plumb" years.

2. A LITTLE HISTORY

The study of the middle atmosphere had its beginnings in the early balloon measurements of *Teisserenc De Bort* [1902], who established that above the troposphere where the temperature decreases with increasing altitude, there existed a region where the temperature became approximately isothermal (i.e., the lower stratosphere). This is nicely seen in Figure 1 of *Goody* [1954], which shows balloon measurements of temperature up to an altitude of about 14 km. Proceeding up in altitude, before the advent of rocket and lidar measurements of atmospheric temperature profiles, the main information on the atmospheric temperature between about 30 and 60 km was from the refraction of sound waves. It was thought curious that the guns fired at Queen Victoria's funeral were heard far to the north of London. Later, during World War I, it was found that the gunfire from the western front was frequently heard in southern England, but there was a "zone of silence" in between where the gunfire was not heard. *Whipple* [1923] explained these observations in terms of the existence of a stratosphere where the temperatures increased appreciably with increasing altitude. It is interesting to note that *Whipple* [1923, p. 87] said the following: "Further progress in our knowledge of the temperature of the outer atmosphere and of its motion would be made if Prof. Goddard could send up his rockets."

In fact, after the end of the World War II, the expansion of the radiosonde balloon network and the use of rockets provided a much better documentation of the temperature and wind structure of the middle atmosphere. *Murgatroyd* [1957] synthesized these measurements, and his Figure 4 shows the very cold polar night stratospheric temperatures (at about 30 km), the warm stratopause temperatures (at about 50 km), and the warm winter mesopause and cold summer mesopause (at about 80 km). Consistent with the thermal wind relation, the wind structure was seen to be dominated by strong winter westerly and strong summer easterly jets centered at about 60 km.

Research into stratospheric ozone can trace its beginnings to the early work of *Hartley* [1881], who correctly attributed the UV shortwave cutoff in solar radiation reaching the ground as being due to stratospheric ozone; to *Chapman*

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[1930], who advanced the first set of chemical reactions for ozone formation and destruction (neglecting catalytic reactions); and to *Dobson and Harrison* [1926], who developed the ground-based instrument for measuring the ozone column that is still being used today. Ground-based measurements [*Götz*, 1931; *Götz et al.*, 1934] and in situ measurements [*Regener*, 1938, 1951] of ozone concentrations clearly indicated that ozone concentrations are highest in the stratosphere.

Early British measurements, using the techniques of *Brewer et al.* [1948], indicated that lower stratospheric water vapor water concentrations are very low (on the order of 10^{-3} times that of the troposphere. These results are summarized by *Murgatroyd et al.* [1955]. Later measurements in the United States indicated larger water vapor concentrations, and this led to some controversy [*Gutnick*, 1961], but the U.K. measurements proved to be correct. This turned out to be very important in establishing the nature of the Brewer-Dobson circulation (as will be seen later), where virtually all tropospheric air enters the stratosphere by rising through the cold tropical tropopause.

This is but a much abbreviated version of the early history of our sources of knowledge of the middle atmosphere well before Alan entered the field. In subsequent sections, we discuss in more detail some previous work in specific areas of research where Alan would be a seminal contributor.

3. WAVE–MEAN FLOW INTERACTIONS

Alan's Ph.D. dissertation in 1972 from the University of Manchester was on the "moving flame" phenomenon, with reference to the atmosphere of Venus. The problem he addressed was the following: Venus's surface rotates once every 243 Earth days, while observations of Venus's cloud tops indicate that the atmosphere at that altitude rotates once every 4–5 days. The question then is by what process does the atmosphere at that level come to rotate so much faster than Venus's surface? A nice explanation of the "moving flame" process is given in *Lindzen*'s [1990] textbook. It basically involves a propagating heat source for gravity waves leading to acceleration at the altitude of this heat source. For Venus, solar heating of the cloud tops is pictured as this propagating heat source.

The *Plumb* [1975] article was largely based on this dissertation work. Among this paper's reference list was the classic paper by *Eliassen and Palm* [1961], who along with *Charney and Drazin* [1961] put forth the famous noninteraction theorem. In the following, some of the results from these classic papers will be briefly reviewed.

The *Charney and Drazin* [1961] paper is a classic. It addresses two important issues: Observations indicate that the scales of stratospheric disturbances were much larger than those seen in the troposphere, so there must be some reason that upward propagating disturbances experience shortwave filtering. The other issue is that while monthly mean stratospheric maps in winter showed planetary-scale wave patterns, such wave patterns were absent during summer.

The first result of the *Charney and Drazin* [1961, p. 83] paper is summarized in its abstract as follows: "It is found that the effective index of refraction for the planetary waves depends primarily on the distribution of the mean zonal wind with height. Energy is trapped (reflected) in regions where the zonal winds are easterly or are large and westerly." To obtain this result, *Charney and Drazin* [1961] derived the following equation for the vertical variations of the perturbation northward velocity in the presence of a mean zonal wind u_0 for quasi-geostrophic flow on a β plane and where the time, longitude, and latitude dependence of the perturbation is $e^{i(kx+ly-kct)}$:

$$(u_0 - c)\frac{\mathrm{d}}{\mathrm{d}z}\left(\frac{\rho_0}{N^2}\frac{\mathrm{d}v}{\mathrm{d}z}\right) - \left[\frac{\mathrm{d}}{\mathrm{d}z}\left(\frac{\rho_0}{N^2}\frac{du_0}{dz}\right) + \frac{\beta\rho_0}{f_0^2 u_c}(u_0 - c - u_c)\right]v = 0, \tag{1}$$

where z is the upward directed vertical coordinate, ρ_0 is the basic state density that only depends on z, N is the Brunt-Väisälä frequency, f is the Coriolis parameter, v is the northward directed wave velocity amplitude, and $u_c = \beta/(k^2 + l^2)$. Letting $\chi \equiv \sqrt{\frac{\rho_0}{N^2}}v$ gives the equation

$$\frac{\mathrm{d}^2\chi}{\mathrm{d}z^2} + n^2\chi = 0, \tag{2}$$

where

$$n^2 = -\left\{\frac{(k^2+l^2)N^2}{f_0^2} + \sqrt{\frac{N^2}{\rho_0}}\frac{\mathrm{d}^2}{\mathrm{d}z^2}\sqrt{\frac{\rho_0}{N^2}}\right\} + \frac{N^2}{u_0 - c}\left\{\frac{\beta}{f_0^2} - \frac{1}{\rho_0}\frac{\mathrm{d}}{\mathrm{d}z}\left(\frac{\rho_0}{N^2}\frac{\mathrm{d}u_0}{\mathrm{d}z}\right)\right\} \tag{3}$$

is the local index of refraction for the problem. Here k is the zonal wave number, l is the meridional wave number, x is the eastward directed coordinate, and y is the northward directed coordinate. *Charney and Drazin* [1961] consider a number of special cases, but the classic case is also the simplest case, where u_0 and $\overline{T}$, the basic state temperature, are constant. In this case, it is easily derived that

$$n^2 = -\frac{1}{4H^2} - \frac{N^2}{f_0^2}\left\{(k^2 + l^2) - \frac{\beta}{u_0 - c}\right\}, \tag{4}$$

where H is pressure scale height. In this case, vertical wave propagation can only occur when $n^2 > 0$ or when

$$0 < u_0 - c < \frac{\beta}{(k^2 + l^2) + (f_0^2/4H^2N^2)} \equiv U_c. \quad (5)$$

This yields the following two famous results. One is that small-scale tropospheric planetary waves cannot propagate a substantial amount into the stratosphere (because $k^2 + l^2$ large implies U_c is small). Thus, vertical propagation can only occur for synoptic scales (i.e., $k^2 + l^2$ large) when $u_0 - c$ is small, implying vertical propagation can occur only in a very narrow window of phase speeds. Also, stationary ($c = 0$) planetary waves cannot propagate through easterlies ($u_0 < 0$)or through strong westerlies ($u_0 > U_c$).

A simple physical interpretation of this result can be seen with the aid of results given by *Pedlosky* [1979]. He showed that the dispersion relation for Rossby waves in a stratified atmosphere is given by the following slight modification of his equation (6.11.6):

$$u_0 - c = \frac{\beta}{k^2 + l^2 + \frac{1}{N^2}\left(m^2 + \frac{1}{4H^2}\right)} \quad (6)$$

where m is the vertical wave number. This gives the familiar result that Rossby waves must propagate westward relative to the mean zonal flow so that stationary Rossby waves cannot exist in an easterly “or westward” flow where $u_0 < 0$. Furthermore, the maximum of $u_0 - c$ occurs for $m = 0$ (infinite vertical wavelength). Thus, the famous *Charney and Drazin* [1961] result of equation (5) can be restated as follows: stationary planetary waves cannot propagate vertically through easterlies (since Rossby waves cannot exist in such a flow), nor can they propagate westward relative to the mean zonal flow at a phase velocity that exceeds the maximum phase velocity for Rossby waves in an atmosphere with constant u_0 and $\overline{T}$.

As an aside, note that the Rossby radius of deformation $L_R \equiv NH/f_0$ for a continuously stratified fluid, so that equation (6) can be rewritten as

$$c = u_0 - \frac{\beta}{(k^2 + l^2) + \frac{1}{4L_R^2}} \quad (7)$$

This is analogous to the case for free barotropic Rossby waves where the $1/4L_R^2$ would be replaced with $1/L^2 \equiv f_0^2/gH$ (where g is the acceleration due to gravity), the reciprocal of the barotropic Rossby radius of deformation squared [see *Holton*, 2004; *Rossby et al.*, 1939].

The second major result of *Charney and Drazin* [1961, p. 83] is stated as follows in their abstract: “. . . when the wave disturbance is a small stationary perturbation on a zonal flow that varies vertically but not horizontally, the second-order effect of the eddies on the zonal flow is zero.” *Charney and Drazin* [1961] say that this result was first obtained by A. Eliassen, who communicated it to them. In the following, we more closely follow the discussions of *Eliassen and Palm* [1961] than those of *Charney and Drazin* [1961].

Eliassen and Palm [1961] considered the propagation of stationary ($c = 0$) mountain waves both when rotation was ignored (i.e., when $f = 0$) and also for the case when $f \neq 0$. For the $f = 0$ case, a more general form of their equation (3.2), for the case of a steady gravity wave propagating with phase velocity c in a shear flow in the absence of diabatic effects, is

$$\overline{p'w'} = -\rho_0(u_0 - c)\overline{u'w'}, \quad (8)$$

where p, u, and w are pressure and horizontal and vertical velocities, respectively, the overbars denote averaging over wave phase, and the primes indicate the wave perturbations. Equation (8) is sometimes referred to as Eliassen and Palm’s first theorem. It implies that for upward wave energy flux ($\overline{p'w'} > 0$), the wave momentum flux ($\rho_0\overline{u'w'}$) is negative when the mean flow u_0 is greater than the phase velocity c and is positive when $u_0 < c$. Thus, any physical process that leads to a decrease of the wave amplitude as it propagates (e.g., dissipation) will force the mean flow toward the wave phase velocity.

For gravity waves with phase velocity $c \neq u_0$, Eliassen and Palm’s second theorem, their equation (3.3), is

$$\rho_0\overline{u'w'} = \text{constant} \quad (9)$$

in the case of no wave transience and no diabatic effects. Thus, in this case, there is no gravity wave interaction with the mean flow.

The implications of Eliassen and Palm’s first and second theorems are far-reaching. They indicate that unless there is dissipation, other diabatic effects, wave transience, or $u_0 = c$, atmospheric gravity waves do not interact with the mean flow. Conversely, if any of these are present, the waves do interact with the mean flow, and this interaction gives rise to a deceleration or acceleration of the mean flow toward the wave’s phase velocity.

The $f \neq 0$ case is more complex. To discuss this, I will use a mixture of results from *Eliassen and Palm* [1961] and *Dickinson* [1969], which reproduce the noninteraction results from *Charney and Drazin* [1961]. Eliassen and Palm’s equation (10.8) can be written as