

Developments in Atmospheric Science 1

F. VERNIANI

Structure and Dynamics of the Upper Atmosphere

ELSEVIER



Developments in Atmospheric Science, 1

STRUCTURE AND DYNAMICS OF THE UPPER ATMOSPHERE

*Proceedings of the 2nd Course of the International School of Atmospheric Physics,
"Ettore Majorana" Centre for Scientific Culture, held in Erice (Italy), 13–27 June, 1971*

edited by

FRANCO VERNIANI

*Institute for Atmospheric Physics of the Italian National Research Council, Bologna; and
University of Bologna, Italy*



ELSEVIER SCIENTIFIC PUBLISHING COMPANY

Amsterdam — Oxford — New York 1974

ELSEVIER SCIENTIFIC PUBLISHING COMPANY
335 JAN VAN GALENSTRAAT
P.O. BOX 211, AMSTERDAM, THE NETHERLANDS

AMERICAN ELSEVIER PUBLISHING COMPANY, INC.
52 VANDERBILT AVENUE
NEW YORK, NEW YORK 10017

Library of Congress Card Number: 72-97437

ISBN 0-444-41105-4

With 339 illustrations and 40 tables

Copyright © 1974 by Elsevier Scientific Publishing Company, Amsterdam

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior written permission of the publisher, Elsevier Scientific Publishing Company, 335 Jan van Galenstraat, Amsterdam

Printed in The Netherlands

Foreword

Thanks to the initiative of Professor A. Zichichi, Director of the "Ettore Majorana" Centre for Scientific Culture, it was possible to set up the International School of Atmospheric Physics and hold its first Course in June 1970. This was followed in June 1971 by a second Course on "Structure and Dynamics of the Upper Atmosphere", that was sponsored by the Italian National Research Council, the Ministry for Public Education, the Ministry for Scientific and Technological Research and the Sicilian Regional Government.

The Course aimed at providing both a comprehensive survey of basic topics like photochemical atmosphere models, tides and gravity waves in the atmosphere, the structure of the various ionospheric regions, the source of atmospheric electrification and a review of some more specialized topics of great current interest and intrinsic importance, such as global observations of the upper atmosphere with meteorological sounding rockets and with remote sensing techniques from satellites, composition studies in the thermosphere by means of mass spectrometers, optical techniques for temperature determination, and radio meteor studies of winds and turbulence in the upper atmosphere.

The Course included ten cycles of lectures and ten seminars for a total of 50 hours. It was attended by 52 participants coming from 17 countries, namely: Argentina, Australia, Belgium, France, Germany, Hong-Kong, India, Israel, Italy, The Netherlands, Norway, Poland, Spain, Sweden, Turkey, The United Kingdom and The United States.

This volume includes most of the material that was presented and discussed at Erice, so I hope the readers will enjoy the book as much as the participants enjoyed attending lectures, seminars and discussions.

Putting together this book was quite a time-consuming task. Mrs. Angelica Ciampi helped me in the revision of the manuscripts, as far as the English language was concerned, Mrs. Maria Teresa Tibaldi typed most of the final typescripts and checked figures and references together with Mrs. Renata Malossi. I wish to thank them very warmly for their invaluable help. Mrs. Tibaldi also acted as secretary of the School and I am grateful to her for the intelligent cooperation in the various stages of the course organization.

Finally, I should like to express my gratitude to Professor Zichichi, Director of the "E. Majorana" Centre, for giving me the possibility to organize the International School of Atmospheric Physics.

Bologna, July 1972

F. VERNIANI

Contributors

Antonio ELENA	Geophysical and Geodetic Institute, University of Genoa, Italy
Giorgio FIOCCO	ESRIN, European Space Research Institute, Frascati (Rome), and University of Florence, Italy
Ewald HARNISCHMACHER	Ionospheric Institute, Breisach, Germany
Egil HESSTVEDT	Institute of Geophysics, University of Oslo, Blindern, Norway
Richard S. LINDZEN	Department of Geophysical Sciences, Harvard University, Cambridge, Massachusetts, U.S.A.
Franco MARIANI	Institute of Physics, University of L'Aquila, CNR Laboratory for Plasma in Space, Rome, Italy
Heinz G. MULLER	Department of Physics, University of Sheffield, Great Britain
William NORDBERG	NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.
Giovanni PERONA	Institute of Electronics and Telecommunications, Politechnic of Turin, Italy
Henry RISHBETH	Radio and Space Research Station, Slough, Great Britain
Gian Carlo RUMI	National Electrotechnical Institute "G. Ferraris", Turin, Italy
Jacek WALCZEWSKI	Hydro-Meteorological Institute, Krakow, Poland
Willis L. WEBB	Atmospheric Science Laboratory, U.S. Army Electronics Command, White Sands Missile Range, New Mexico, U.S.A.
Ulf von ZAHN	Institute of Physics, University of Bonn, Germany

Co-authors

Glauco BENEDETTI-MICHELANGELI	ESRIN, European Space Research Institute, Frascati (Rome), Italy
Mario BOSSOLASCO	Geophysical and Geodetic Institute, University of Genoa, Italy
Giorgio CAPPUCCIO	ESRIN, European Space Research Institute, Frascati (Rome); now at the Institute for Atmospheric Physics, Rome, Italy
Fernando CONGEDUTI	ESRIN, European Space Research Institute, Frascati (Rome), Italy

Donald F. HEATH	NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.
Ernest HILSENATH	NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.
Arlin J. KRUEGER	NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.
Cuddapah PRABHAKARA	NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.
John S. THEON	NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.

Developments in Atmospheric Science, 1

Structure and Dynamics of the Upper Atmosphere

Contents

Foreword	V
Contributors	VII
G. Fiocco: IMPACT OF MODERN TECHNOLOGY ON THE ATMOSPHERIC SCIENCES (Opening speech)	
E. Hesstvedt: PHOTOCHEMICAL ATMOSPHERE MODELS	
Summary	5
1. Introduction to photochemical atmosphere models	5
2. A time-dependent photochemical model of the upper stratosphere and lower mesosphere	10
2.1. Introduction	10
2.2. The photochemical model	10
2.3. Results	10
2.4. Conclusion	17
References	18
R.S. Lindzen: TIDES AND INTERNAL GRAVITY WAVES IN THE ATMOSPHERE	
Summary	21
1. History of the study of tides and elementary physics of internal gravity waves	21
1.1. Introduction	21
1.2. History	22
1.3. Elementary physics of internal gravity waves	26
2. Atmospheric tides: data	31
3. Atmospheric tides: theory	39
3.1. Assumptions, approximations and equations	39
3.2. Mathematical methods of solution	54
3.3. Explicit calculation of atmospheric tides	58
3.4. Solar diurnal thermal tide	62
3.5. Lunar semidiurnal tide	68
3.6. Comparisons with data	69
4. Further developments	70
4.1. Neglect of mean winds and horizontal temperature gradients	71
4.2. Neglect of dissipation	74
4.3. Nonlinear effects	79
4.4. Tides in the thermosphere	79
References	85
W.L. Webb: ELECTRICAL STRUCTURE OF THE LOWER IONOSPHERE	
Summary	89
1. Introduction	90
2. Diurnal circulations	94
3. Electrical processes	99
4. Electrical structure	102
5. D and E regions	118
6. Atmosphere conductivity structure	121
7. The dynamo currents	123
8. Conclusions	124
References	126

D.F. Heath, E. Hilsenrath, A.J. Krueger, W. Nordberg, C. Prabhakara and J.S. Theon: OBSERVATIONS OF THE GLOBAL STRUCTURE OF THE STRATOSPHERE AND MESOSPHERE WITH SOUNDING ROCKETS AND WITH REMOTE SENSING TECHNIQUES FROM SATELLITES

Summary	131
1. Introduction	132
2. Techniques for measuring the composition, thermodynamic structure and motion field of the neutral atmosphere up to 80 km	134
2.1. Rocket techniques	134
2.2. Satellite techniques	139
3. Results of observations	146
3.1. The mean thermodynamic structure and circulation of the mesosphere from rocket soundings	146
3.2. Small-scale and short-term variations in the vertical structure of the mesosphere	153
3.3. Temperature structure in the noctilucent clouds	159
3.4. Global stratospheric temperature fields observed with satellites	164
3.5. Global ozone fields from satellite observations	175
3.6. Nocturnal structure of O_3 in the mesosphere	179
3.7. Results of atomic oxygen sounding	188
3.8. Long-term variations of solar UV energy inputs to the mesosphere	189
References	194

J. Walczewski: UPPER ATMOSPHERE ROCKET SOUNDINGS IN POLAND

Summary	199
1. Introduction	199
2. Rockets, instrumentation and sounding schedule	199
3. Results	201
References	202

G. Benedetti-Michelangeli, G. Cappuccio, F. Congeduti and G. Fiocco: ACTIVE AND PASSIVE OPTICAL DOPPLER TECHNIQUES FOR THE DETERMINATION OF ATMOSPHERIC TEMPERATURE, 1: AN AIRGLOW SPECTROPHOTOMETER WITH INTERNAL LASER REFERENCE

Summary	205
1. The airglow spectrophotometer	205
References	210

G. Benedetti-Michelangeli and G. Fiocco: ACTIVE AND PASSIVE OPTICAL DOPPLER TECHNIQUES FOR THE DETERMINATION OF ATMOSPHERIC TEMPERATURE, 2: A HIGHLY COHERENT LASER RADAR

Summary	211
1. Characteristics of the laser radar	211
References	219

E. Harnischmacher: MORPHOLOGY OF THE LOWER IONOSPHERE

Summary	221
1. The D region	221
1.1. Methods of observation	221
1.2. Electron density profiles	230
1.3. Multifrequency absorption over Freiburg "A1"	231
1.4. Relation between ionospheric absorption and solar activity	238
1.5. Seasonal effects in the relationship between absorption and magnetic disturbance character	243
1.6. Solar radio noise flux effects	244

2. The normal E layer	245
2.1. Methods of observation and layer parameters	245
2.2. Statistical treatment for parameters with diurnal, seasonal and year-to-year variations	262
3. The sporadic E layer	272
3.1. Methods of observation and principal parameters of the Es layer	272
3.2. The global behaviour of Es	277
3.3. The fine structure of Es over Europe	280
3.4. Es parameters over Freiburg, compared with the f_oE 50% as a standard	291
3.5. Statistical analysis concerning the Es classification evaluated at Freiburg	297
3.6. The day-to-day variation of f_oEs over Europe	302
3.7. The variation of $h'Es$	312
References	316
Bibliography	316

G.C. Rumi: TECHNIQUES FOR THE MEASUREMENTS OF THE ELECTRON DENSITY AND TEMPERATURE IN THE D REGION

Summary	321
1. Foreword	321
2. The cross-modulation technique	323
2.1. Introduction	323
2.2. Theoretical compendium	325
2.3. Experimental results	329
3. The LF technique	332
3.1. Introduction	332
3.2. Theoretical developments	333
3.3. Experimental evidence	335
4. Conclusion	338
References	339

M. Bossolasco and A. Elena: MID-LATITUDE SPORADIC E

Summary	341
1. Introduction	341
2. Data and method	341
3. The spatial correlation of the Es layer	342
4. Discussion	343
References	345

H.G. Muller: WINDS AND TURBULENCE IN THE METEOR ZONE

Summary	347
1. Radio meteor techniques for the study of upper atmospheric winds	348
1.1. Introduction	348
1.2. The basic principle of observation	349
1.3. C.W. radar techniques	351
1.4. Pulsed techniques	352
1.5. Comparison between C.W. and pulsed techniques	355
1.6. Problems associated with the determination of individual wind components	358
1.7. Measurements of wind shears in single station experiments	359
1.8. The utilisation of multiple reflections from a meteor trail	360
1.9. On the possibility of a network of meteor wind stations on a global scale	360
2. Neutral winds in the meteor zone	362
2.1. Introduction	362
2.2. The general structure of the upper atmospheric wind	363
2.3. The resolution of individual components in the upper atmospheric wind	364

2.4. The prevailing wind	367
2.5. The periodic tidal wind	367
2.6. Short-period oscillations in the wind	370
2.7. Long-period oscillations in the wind and the connection with other atmospheric parameters	371
3. Wind shears and turbulence in the meteor zone	375
3.1. Introduction	375
3.2. The nature of the irregular component of the upper atmospheric wind	377
3.3. The examination of the characteristics of turbulence at meteor heights	379
3.4. The diurnal and seasonal variation of shear and turbulent parameters	384
References	387

U. von Zahn: COMPOSITION STUDIES IN THE THERMOSPHERE BY MEANS OF MASS SPECTROMETERS

Summary	389
1. Upper atmospheric processes investigated in situ by means of mass spectrometers	389
1.1. Introduction	389
1.2. Altitude dependence of pressure and number densities below 85 km	390
1.3. Altitude dependence of number densities and composition above 85 km	392
2. Technological aspects and instruments	404
2.1. General problem areas	404
2.2. Instruments	409
2.3. Calibration procedures	416
3. Discussion of results obtained so far	423
3.1. Mean value of number densities at 150 km altitude	423
3.2. The problem of atomic oxygen	424
3.3. Height of turbopause and eddy diffusion coefficients	426
3.4. Diffusive equilibrium	426
3.5. Helium and vertical transport	427
3.6. Wave phenomena and the geomagnetic activity effect	430
4. The outlook for future studies	430
References	431

H. Rishbeth: STRUCTURE OF THE F REGION AND GLOBAL THERMOSPHERIC WINDS

Summary	435
1. Observations of the F region	435
1.1. Introduction	435
1.2. Experimental methods	436
1.3. Features of the undisturbed F layer	440
1.4. F-layer disturbances	446
2. A resume of the F-region theory	448
2.1. The composition of the atmosphere and ionosphere	448
2.2. Production of ionization	451
2.3. F-region chemistry	453
2.4. Motions of ionization	456
2.5. Formation of the F2 peak	459
3. Global thermospheric winds	461
3.1. The global distribution of thermospheric temperature	461
3.2. The equations governing thermospheric wind velocities	462
3.3. The wind systems	465
3.4. Large-scale transport of air by winds	467
3.5. Effects of winds on the F2 layer	469
3.6. Some outstanding problems	474
References	476

M. Bossolasco and A. Elena: MID-LATITUDE IONOSPHERIC IRREGULARITIES

Summary	481
1. Introduction	481
2. The pre-sunrise maximum in the F2 region	481
3. Baylike disturbances in the F2 region	485
4. Discussion	487
References	489

G.E.Perona: ELECTRONS PRECIPITATING INTO THE D REGION FROM THE INNER AND OUTER VAN ALLEN ZONES

Summary	491
1. Introduction	491
2. Precipitation of electrons during magnetically quiet periods	493
3. D-region perturbations from precipitating electrons	496
4. Precipitation during magnetically disturbed periods	497
5. Conclusions	499
References	500

F. Mariani: CORPUSCULAR EFFECTS IN THE IONOSPHERE

Summary	503
1. Introduction	503
2. The maintenance of the night ionosphere	504
3. Long-term variations of the ionospheric electron density and correlations with solar activity	507
4. Temperature effects	509
4.1. Neutral and charged particle temperatures	509
4.2. Photoelectron drift and conjugate effects	511
5. Conclusions	520
6. Appendix	520
References	522

Author Index	525
Subject Index	533

Opening Speech:

IMPACT OF MODERN TECHNOLOGY ON THE ATMOSPHERIC SCIENCES

GIORGIO FIOCCO

Università di Firenze and European Space Research Institute (ESRIN), Frascati (Italy)

I am going to restrict myself to some opening remarks that will be neither too specific nor too technical. I have chosen a title which is vague enough, perhaps a little banal, but which I hope describes some general aspects of the work in the atmospheric sciences.

The impact of technology means that a very substantial level of resources is now available to disciplines, some of which, only one or two decades ago, utilized rather simple instrumentation and, often, empirical methods of analysis. On the other hand, it may also mean that a very large part of those resources is used in solving technical problems, when a certain amount of ingenuity in the definition of the scientific aspects of the problem might have saved time and effort.

In our culture it is often not clear whether the offer of a product or a service is in response to a need, or whether demand is being artificially created. Judging the validity of scientific research is not simple. A criterion should be based on a reasonable compromise among originality, usefulness and cost. This does not mean that a piece of work should be trivial or useless as long as it is expensive. Rather the opposite! As far as usefulness goes, the atmospheric sciences come out rather honourably.

I assume that many of those attending this school are, like myself, from Western Europe. Since for the last several years most of the scientific effort has been carried out in the U.S. and the U.S.S.R., the choice among originality, usefulness and cost for the European scientist has been, and still is, more limited. With low cost being a sort of boundary condition, let us try at least to be original and useful.

In the atmospheric sciences, as in other sciences that have emerged from the stage of taxonomy, results are obtained by a competition between (analytic, numerical) models and experiments. One practical example is weather prediction. Numerical models are developed by digital computers; data are collected by a worldwide network, and now also by satellites. At least twice a day several weather bureaus turn out forecasts, the validity of which is tested by a multitude of users. Originality may not be too high, and individual contributions may disappear in much routine

work, but the usefulness is great and the cost is high.

Although the mathematical and physical sophistication of the model utilized is not great, the organization necessary to carry out the scheme is very complex.

It appears, by the way, that the prediction of an experienced forecaster is not much worse than that carried out by the computer. On the basis of the preliminary computer analysis, the forecaster can make an even better prediction. Thus, one wonders whether some aspects of this extremely laborious computation could be replaced either by more powerful mathematical techniques or by better understanding of how the human mind works.

In practice, now, progress in weather forecasting is closely related to progress in computers. But notice that the cost of a commercially available, advanced computer of medium size can be 10^7 \$ or a monthly rental of approximately $2 \cdot 10^5$ \$. After considering, for example, that a reduction by a factor of 2 in the size of the computational grid involves an increase by a factor close to 2^4 in the computer size, it becomes obvious that many of the problems in the atmospheric sciences cannot be solved by sheer strength of computation in the foreseeable future. In this spiral of high costs, the question of international cooperation also becomes essential. At the moment there are more than ten agencies in the world that carry out detailed weather predictions. Several of these are in Europe; in this case there is an evident overlap even for short-term predictions. Therefore, the establishment of common centers is becoming mandatory. Of course, the establishment of large facilities should make global weather predictions possible and allow some of the available computer time to be dedicated to research. Thus, it should be possible to study in detail, for instance, the kind of problems that Professors Hesstvedt and Lindzen discuss in their contributions.

When global predictions are considered, one of the difficulties is lack of adequate data, especially for the Southern hemisphere, the oceans, and the less populated areas. Satellites perform very well as far as global coverage is concerned. The instruments carried by the present generation of meteorological satellites permit: (1) Continuous observation of the earth's cloud cover; (2) Infrared sounding of the atmosphere to allow quantitative deviation of vertical temperature profiles; (3) Infrared scanning to study the earth's radiative budget.

With this basic instrumentation, aided also by rocket campaigns, a fairly complete description of the mesospheric and stratospheric meteorology has emerged. The measurements at tropospheric levels are more difficult to interpret. Synoptic observations of cloud formations are of interest to the weather forecaster. They permit, for instance, the early detection of severe storms, especially since the area observed may not be adequately covered by ground stations. This information is of a qualitative nature and some scientists have tended to de-emphasize its importance. Cloud movements are, of course, an aid to the measurement of wind velocity, even though doubts may remain in some cases as to whether clouds move

at the same velocity as the wind. Cloud heights, also, are not measured directly.

As we shall see in Dr. Nordberg's lectures, the measurement of atmospheric temperature profiles from the CO_2 15- μ emission band was one of the important results. The contributions to the total spectral density measured on the satellite come from different height levels, so that for each portion of the spectrum a different weighting function exists. The problem of data reduction involves the inversion of raw data—an operation which can be ambiguous. The contribution of clouds and aerosols sets a limit to the present accuracy of the technique. The problem arises of making observations through holes in clouds, or making use of different spectral regions.

The possibility of detecting minor atmospheric constituents is still at the experimental stage. This is also of importance to the circulation of pollutants and other ecological problems. I suspect that a good deal of work is still necessary in order to develop adequate sensors and to prepare the atmospheric models necessary for the interpretation of data. The study of more complex compounds, such as the polymers of water, clusters and aerosols, is also attracting great interest. Satellites can be used to communicate with buoys, to track floating balloons, and to relay data from ground stations and data centers. But just to give some idea about cost: an estimate for a satellite including the development of the sensors, ground stations, etc., may run over $5 \cdot 10^7$ \$.

A rapid survey like this should not neglect the use of the manned orbiting laboratory, especially with regard to the testing of particularly complex instrumentation: but here, the question of costs may really get out of hand.

Last, but not least, I should call your attention to the important work that can be done with relatively inexpensive ground-based instruments, such as the meteor radars. In this connection, I will give a seminar on the laser as a tool for atmospheric studies. This is, of course, only one of the main tools that the atmospheric scientist has at his disposal today.

Let us remember that knowledge about the earth's atmosphere is important in many facets of human activity, from strictly economic ones to more speculative ones. For instance, exact geodetic surveys carried out from satellites equipped with corner reflectors, or from the moon itself, are limited by our knowledge of the refractive index of air. Fluctuations in air properties should be better known if accuracies of the order of a few cm, which are technically feasible, are to be achieved. I do not have to expound further on the vast importance of accurate climatological studies and weather predictions. Therefore, having established proper priorities, it is clear that the field of atmospheric study is not only scientifically valid, but also of great practical relevance.

PHOTOCHEMICAL ATMOSPHERE MODELS

EIGIL HESSTVEDT

Institute of Geophysics, University of Oslo, Blindern (Norway)

SUMMARY

The first section describes how a photochemical atmosphere model is built up. Definitions are given of basic concepts such as reaction and dissociation rate coefficients and lifetimes. The pure oxygen atmosphere model is used as an example. The necessity of considering atmospheric transport together with chemistry is emphasized.

In section 2 the principles given in section 1 are applied to an oxygen-hydrogen model in order to study the composition of the upper stratosphere and lower mesosphere. The computation of ozone is in fair agreement with observational data and turns out to be of particular interest.

1. INTRODUCTION TO PHOTOCHEMICAL ATMOSPHERE MODELS

An efficient study of the upper atmosphere depends, to a large extent, upon our knowledge of its chemical composition. During the last few years a series of measurements has provided us with useful information, but the situation is still far from satisfactory, even for such important trace components as atomic oxygen, ozone, nitric oxide and water vapor.

In addition to experimental results, useful information can be obtained from photochemical models. In such models, one tries to simulate the chemistry of the real atmosphere by specifying a set of chemical reactions which are believed to be important for the problem to be studied. In the more recent models, the effect of vertical air transport has been included as well. There are two kinds of reactions:

(a) chemical reactions, e.g.:

