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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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AGARD ADVISORY REPORT No. 24

on

The Aerodynamics of Atmospheric Shear Flows

by

J. E. Cermak and B. W. Marschner

NORTH ATLANTIC TREATY ORGANIZATION

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J.E.Cermak and B.W.Marschner
6 pages
Published May 1970

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This report reviews the purpose, scope and conclusions of the meeting, which was stimulated by the need to coordinate the efforts of atmospheric scientists and aeronautical engineers, through the common language of fluid dynamics, in attacking the basic and applied problems of atmospheric

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THE AERODYNAMICS OF ATMOSPHERIC SHEAR FLOWS

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by

⑧ J. E. Cermak and B. W. Marschner ⑨

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CONTENTS

THE AERODYNAMICS OF ATMOSPHERIC SHEAR FLOWS

J.E.Cermak and B.W.Marschner

1. INTRODUCTION

The AGARD Specialists' Meeting on the Aerodynamics of Atmospheric Shear Flows was sponsored by the Fluid Dynamics Panel which was chaired by Professor R.N.Cox, UK. This meeting was held in Munich, Germany during the period 15-17 September, 1969. Members of the Program Committee were Professor A.D.Young, UK (Chairman); Mr.E.Dobbinga, Netherlands; Professor J.J.Ginoux, Belgium; Professor B.W.Marschner, USA; Professor E.Truckenbrodt, Germany; and Professor J.Valensi, France. Papers presented at the meeting are appended to this report as a list of references.

Stimulation for this meeting was provided by a Round-Table Discussion on Industrial Aerodynamics held in Göttingen, Germany on 14 September, 1969, following the AGARD Specialists' Meeting on Fluid Dynamics of Rotor and Fan-Supported Aircraft at Subsonic Speeds. This discussion was under the chairmanship of Dr.R.C.Pankhurst, UK, with presentations given by Professor E.Truckenbrodt, Germany; Mr.E.Dobbinga, Netherlands; Professor J.E. Cermak, USA; Professor J.Valensi, France; Professor J.J.Ginoux, Belgium; Professor J.L.Taylor, Norway; and Dr.E.W.E.Rogers, UK. General topics discussed at the Round-Table Discussion which were later excluded from this meeting were the following: flow in ducts, unsteady multi-phase flows, medical and biological aerodynamics, agricultural aerodynamics, and aerodynamics of fans.

The objective of this report is to place the over-all contibutions of this meeting into perspective with regard to needs for further research and development required to reach a fundamental understanding of the subject matter and/or to adequately cope with the related practical applications. Hopefully, if this understanding can be achieved in an objective manner, this report can provide guidance to AGARD personnel for stimulation of new research in certain areas.

Following the program of paper presentations as shown in the list of references, a Round-Table Discussion was convened to summarize the meeting and to give all participants an opportunity to comment. The panel consisted of Professor B.W.Marschner*, USA (Chairman); Professor J.E.Cermak, USA; Professor H.Panofsky, USA; Professor R.S.Scorer, UK; and Mr.C.Scruton, UK. The discussion was opened to all participants after each panel member presented a brief prepared summary. These summary statements and discussions were transcribed and will appear as part of the AGARD Conference Proceedings No.48. Therefore, this report will not dwell on a review of the meeting but will focus on the previously stated objective.

Specific Conclusions and Recommendations are presented following a statement of the Purpose and Scope of the Meeting and a Program Evaluation.

2. PURPOSE AND SCOPE OF MEETING

Many aeronautical problems arise as a result of atmospheric motion near the earth's surface. The stability and control of aircraft during take-off and landing; the location and design of landing sites for VSTOL aircraft, especially helicopters, in and near cities; ground-air communications by transmission of electromagnetic energy; transmission of aircraft-generated noise to populated areas; the visibility limitations imposed by fog and smog; and the behaviour of high-speed aircraft moving through gravity-wave systems are a few well known examples. In each case the time and space variability of wind velocity or refractive index or density is a key factor in the problem. The characteristics of variability in these quantities within the atmospheric surface layer, i.e., turbulence and gravity-wave structure, are strongly affected by stratification of the mean atmospheric temperature, vertical wind shear and the surface features of topography, buildings, trees, etc. Another important aeronautical problem arises from the occurrence of clear-air turbulence. Although this problem arises most often at elevations above the atmospheric surface layer, the main cause appears to be associated with intense wind shear and thermal stratification just as for the problems encountered at lower levels. Thus, the disciplines of micrometeorology and mesometeorology related to thermally-stratified shear flows are vitally important to the aeronautical engineer.

During the last decade important advances in micrometeorology and mesometeorology have been made through greatly accelerated research efforts stimulated by applications to non-aeronautical problems†**. Many of these

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* Professor Marschner replaced Professor Truckenbrodt who could not attend due to illness.

† Proceedings of an International Symposium on Boundary Layers and Turbulence with Geophysical Applications, 19-24 September 1966, Kyoto, Japan. Published in *Physics of Fluids* 10, No.9, September 1967 (edited by K.F.Bowden, F.N.Frenkiel and I.Tani).

**Proceedings IUCRM Colloquium on Spectra of Meteorological Variables, 9-19 June 1969, Stockholm, Sweden, Published in *Radio Science*, December 1969.

advances in knowledge have been achieved through cooperative efforts of atmospheric scientists and fluid dynamicists, particularly, in the area of laboratory simulation of atmospheric motions. Accordingly, it was highly appropriate for the Fluid Dynamics Panel to organize a meeting to simulate application of new knowledge and techniques in meteorology on micro- and meso- scales to aeronautical problems.

In essence, the primary purpose of the meeting was to stimulate communication between atmospheric scientists and aeronautical engineers through the common language of fluid dynamics. The objectives of this communication were to establish what is known about motions of the atmosphere near the earth's surface, to state the basic problems related to such flows and to examine some of the applications to industrial problems which may have aeronautical interest.

The scope of subject matter covered by the meeting is rather well defined by its title "Aerodynamics of Atmospheric Shear Flows". Primary emphasis was placed on motion in the atmospheric surface layer. Secondary consideration was given to shear layers at high altitudes (clear-air turbulence) and shear flow over mountainous topography (mountain lee-waves). Within this range of subject matter the papers were confined to the following three topical areas:

I. Flow structure - turbulence, mean motion

II. Basic problems - diffusion, similarity, and laboratory simulation

III. Industrial problems - wind forces on structures, diffusion.

The chosen scope of material provided ample opportunity for development of significant contributions of aeronautical interest. Other related subject matter having important aeronautical applications, such as strong convective motions and thunder-storms, were excluded. A future meeting could be devoted profitably to these two topics.

3. PROGRAM EVALUATION

This evaluation attempts to analyze the contributions of the meeting with regard to completeness of fundamental knowledge and adequacy for treatment of the applied problems. Where possible, directions for further research are identified. Unfortunately, this evaluation reflects the writers' strengths and weaknesses in this subject matter; therefore, each reader should moderate these comments with his personal knowledge and experiences in the field.

3.1 Structure of Atmospheric Shear Flows

Papers 1, 5, 6 and 8 give valuable information on micro-structure of turbulent shear flows, particularly from the view-point of similarity theory. Agreement of vertical velocity fluctuation spectra with Monin-Obukhov similarity in the surface layer (from an elevation of about z_0 to 30m) is a useful result which simplifies the specification of shear and thermal stratification on vertical turbulence. However, such agreement has been verified only for flow over flat boundaries of uniform roughness and temperature which leads to plane homogeneous turbulence. This means that for flow over surfaces of non-uniform roughness, temperature and vertical relief no confidence can be placed on this result. We must ask questions such as how far downstream from a change in boundary conditions will the Monin-Obukhov similarity be restored or, for a flow separated in passing over a hill or structure, how far downstream from reattachments will similarity be restored? Research in both the laboratory and the field will be required to answer such questions. On the other hand, Monin-Obukhov similarity fails for longitudinal and lateral velocity fluctuation spectra. This finding opens an interesting but difficult area for investigation - relating the long wave-length longitudinal and lateral velocity fluctuations to the geometry of distant upwind meso-scale topographic features and/or convection of large-scale longitudinal vortices discussed in Paper 20.

No contributions were presented on the turbulence characteristics of wakes in the atmosphere downstream from buildings, hills, patches of trees, etc. Information on interacting shear flows is badly needed before some of the aeronautical problems listed in the introduction can be attacked successfully. The study reported in Paper 16 is a sample of the type of research required. However, this must be expanded to include field measurements and laboratory measurements in wind-tunnels capable of simulating the turbulence characteristics as well as the mean velocity characteristics of oncoming atmospheric flows.

Paper 7 introduces a mechanistic model for treating turbulent flows in which the mean velocity gradient becomes zero or the mean flow field becomes three-dimensional. Since these features are generally present in atmospheric shear flows, further development and verification of the model should be undertaken in spite of its complexity.

Stratified atmospheric flow over complex terrain produces strong gravity wave systems such as those described in Paper 3. Extensive analytical and experimental research efforts have been devoted to the study of this type of flow over simple *two-dimensional* ridges*. However, attempts to study such flows over real topography (three-dimensional systems) have been very few. For this reason, Paper 11 represents an extremely important development

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* Proceedings of a Symposium on Mountain Meteorology 26 June 1967, Colorado State University, Fort Collins, Colorado. Atmospheric Science Paper No.122 (Edited by E.R.Reiter and J.L.Rasmussen).

in the capability to describe complex flow structure over mountainous and hilly terrain. The present form of the model described in Paper 11 does not include surface shear effects: therefore, it is capable of predicting flow structure on the meso-scale but not on the micro-scale.

The occurrence of clear-air turbulence at high altitudes often results from instability of stratified shear layers such as those described in Paper 4. Mechanisms for the development of instability in these layers are described in Paper 2. The authors of both Papers 1 and 2 suggest that mountain lee-waves can perturb the upper-level shear layers and produce instability which leads to clear-air turbulence. Strong convective motions may also produce instability of the stably stratified shear layer. For application to the planning of aircraft flight routes it follows that the capability to forecast mountain lee-wave development must be cultivated. This subject was not discussed at the meeting; however, other conferences* have considered the prediction problem. Atmospheric gravity waves can also be created from flow over a flat terrestrial surface of non-uniform temperature which produce a "heat-mountain". No contributions on "heat-mountain" lee-wave formation were presented at the meeting. Much help is needed from the atmospheric scientist to help an unsuspecting pilot anticipate clear-air turbulence which may be triggered by such a phenomenon.

3.2 Basic Problems Related to Atmospheric Shear Flows

One class of basic problems related to atmospheric shear flows is centered about the extension of our knowledge on classical shear flows to account for complicating features encountered in the atmosphere. The dominant features of concern are thermal stratification, high roughness elements (forests and cities), non-uniformity of surface roughness and/or surface temperature, non-planar boundaries (hills and mountains), rotation of the flow system, and unsteadiness of the boundary conditions. These features complicate analytical efforts to the point of frustration. Therefore, the study of simulated atmospheric shear flows in the laboratory to acquire both basic knowledge and the solution to specific problems, has been developed intensively during the last decade. Contributions to this section of the meeting - Papers 12, 13, 14, 15, 17, 18, and 22 - reveal that this approach can be of great value.

Special laboratory facilities and simulation techniques have not been developed which can be used to simultaneously study the effects of all the features listed in the preceding paragraph. For example, special meteorological wind tunnels like the one shown in Paper 12 can simulate many micro-scale features of atmospheric surface layers or large-scale flow features on the meso-scale; however, micro-scale motion cannot be simulated currently in a model scaled to study mesometeorological motions. This means that the investigator of a basic atmospheric-shear-flow problem must design his experimental facilities to optimize similarity for the scale of motion he wishes to study. On any scale, compromise with exact similarity is usually necessary. A challenge for the future is to become able to estimate the consequences of approximations to exact similarity when the simulated flow is used in the study of a particular problem.

In the study of micro-scale motions of the atmospheric surface layer in a wind tunnel only partial similarity is attained because of Reynolds number limitations. This difficulty has motivated many efforts to synthesize the structure of shear layers in a manner which maximizes the effective Reynolds number. The long test-section wind tunnel such as referred to in Papers 12 and 17 yields satisfactory results; however, such facilities are costly and cannot be developed easily from existing aeronautical type wind tunnels. Accordingly, efforts to utilize short test-section wind tunnels by introducing grids, screens and/or vortex generators such as described in Papers 13, 14 and 16 are common. The results given in Paper 14 indicate that a system based on large longitudinal vortex generators has promise of yielding the flow characteristics desired with a modest length of working section.

The stability of stably stratified shear layers introduces another important class of basic problems. Paper 15 presents the results of a coordinated effort to study these flows by the use of analysis, laboratory simulation and field data. This paper not only provides definitive results but offers an excellent example of how studies of atmospheric shear flows can be made complete by combining the results of analysis, laboratory studies and field measurements.

Turbulent diffusion constitutes a class of basic problems which has been studied in the laboratory and in the atmosphere with similarity theory providing a basis for comparison of data. Paper 21 presents a significant advance in the application of the Lagrangian similarity hypothesis in the atmospheric surface layer. By taking into account that the lateral turbulence level is not uniquely specified by local similarity parameters an additional parameter σ_v/u_* is introduced into the analysis. This extended similarity formulation gives predictions which are in excellent agreement with the data obtained from the diffusion experiments of Project Prairie Grass. The question of what is the appropriate value of σ_v/u_* for a particular site and specific meteorological conditions is still open. When diffusion through the entire planetary boundary layer must be dealt with, the analysis presented in Paper 19 offers a promising approach.

Fluid dynamical effects produced by rotation of the earth introduce some interesting basic problems. In the case of an atmosphere with unstable density stratification longitudinal vortices are shown to form which are analogous to the classical Taylor-Gortler vortices - Paper 20. These motions should have a profound effect on diffusion in the atmosphere; however, no known diffusion model accounts for such motions. Additional research should be devoted to a determination of how the strength of longitudinal vortices varies in time.

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* Proceedings of a Symposium on Clear Air Turbulence and Its Detection, 14-16 August 1968, The Boeing Company, Seattle, Washington. Published by Plenum Press, 1969 (Edited by Yih-Ho Pao and A.Goldburg).

3.3 Industrial Problems Related to Atmospheric Shear Flows

Problems of direct aeronautical applications were excluded from the group of contributed papers on industrial problems. Thus, the many problems associated with flight dynamics during take-off and landing were not considered. However, the kinds of industrial problems discussed at the meeting were selected because of their importance relative to the support of aeronautical activities.

Non-aeronautical industrial problems related to atmospheric shear flows are encountered primarily in the atmospheric surface layer. These include wind loading on structures; diffusion associated with air pollution problems; wind-shelter design; dispersion of air released insecticides and fertilizers; evaporation of water from water surfaces, soil and plants; wind generated movement of soil, water and snow; dispersion of electromagnetic energy; etc. Papers 23 through 27 treated only the first three of these topics with major emphasis on problems related to wind loading on structures.

Paper 23 provides an excellent review of wind loading on structures. The greatest difficulty in the analysis of such problems is related to the scarcity of appropriate types of wind data, particularly in city complexes. Since the collection of appropriate statistical wind data by meteorologists within city complexes for use by structural engineers is an almost impossible task another approach is necessary. The approach which has been used to study loading on recently proposed monumental structures is to measure directly wind loading on a model of the structure surrounded by a model of the city over which a simulated wind is generated in a wind tunnel. In this approach the meteorologist is called upon for information about the large-scale wind motion (direction, speed and stability) to be expected for the area. Using the most severe of these winds as ambient flows over the model, information on local wind statistics is provided by the aerodynamicist from measurements in the simulated flow. A need still remains for a well coordinated laboratory and field study in which the same wind statistics are measured in the prototype and model flows. The data could be analyzed on a comparative basis to determine how faithfully the model simulates actual local wind structure.

The new experimental data on drag response of a flat plate as a function of the non-dimensional frequency (nD/V) and relative longitudinal-integral turbulence scale (L_x/D) presented in Paper 24 is, indeed, welcome. Provided the upwind turbulence structure is known, the results presented can be used to give at least a first approximation to wind forces on the upwind face of large buildings. Further research on this problem should include a systematic study on the effect of the relative lateral-integral turbulence scale L_y/D on both drag response and moment response.

No new results were presented on how to predict concentration of pollutants downwind from power plant and other industrial smoke stacks. When the atmosphere is strongly stratified, either stably or unstably, or the plume is strongly heated or cooled (by wet-scrubbing) no reliable prediction methods are available. The fluid dynamicist should find this problem both challenging and rewarding.

4. CONCLUSIONS

The meeting accomplished well the primary purpose for which it was intended - stimulation of communication between atmospheric scientists, aeronautical engineers and fluid dynamicists. Evidence that the meeting was timely and appropriate is given by the subdued discussion, primarily by that part of the delegation composed of aeronautical engineers, following many papers devoted to topics on structure of atmospheric shear flows. This observation also suggests that, aside from the review paper, the atmospheric scientists assumed a greater familiarity with the subject matter by the group than was actually warranted. One or two of the research papers on structure of atmospheric shear flows sacrificed for the same number of review papers could have enhanced the intended communication process.

Papers contributed to the meeting revealed that characteristics of the atmospheric surface layer over level homogeneous surfaces of large extent are well established. However, in the more usual circumstances where the uniform surfaces are made non-uniform by one or more factors such as temperature, high roughness elements (trees, buildings, etc.), and topography very little knowledge of flow structure which is generally applicable is known. The complex boundary conditions develop flows having large spatial variability which is highly significant to many aeronautical applications. This situation presents to the atmospheric scientists a challenge for establishment of basic knowledge on the space variability of atmospheric variables through simultaneous multiple-point sensings distributed over a three-dimensional grid.

Contributions from fluid dynamicists documented an ever increasing use of laboratory studies to investigate both basic and applied problems related to atmospheric shear flows. Simulation of the atmospheric shear flows has been approximated sufficiently well, particularly for micro-scale motions, to permit useful velocity space-variability studies to be accomplished in the laboratory. This type of atmospheric modeling can be used to determine flow structure in urban complexes, in wakes downwind of structures, in forest clearings, and near wind breaks. No other approach to obtain such data appears to be feasible; therefore, efforts to improve the atmospheric simulation capability of laboratory facilities should be encouraged.

A greater effort should be made to communicate to meteorologists the type of wind data needed by aeronautical engineers. Exceedance statistics - e.g., the probability that the difference in vertical wind speed at two points will exceed prescribed values - for particular meteorological and surface conditions are badly needed. The presentation of a review paper in the industrial problems session on a subject such as analysis of airfoil response to gusts would have helped generate discussion on the kinds of wind data desired.

5. RECOMMENDATIONS

(a) The quality of the environment in all of the NATO countries is becoming an issue of vital importance. Hence, it appears that the fluid mechanics panel must take a more active role in the area of atmospheric flows as they pertain to questions of pollution, flight problems, and other local phenomena.

(b) Knowledge on atmospheric shear flows is expanding rapidly through research on many frontiers of importance to aeronautical applications. The capabilities for numerical simulation and laboratory simulation of these flows are being developed in many countries; therefore, the Fluid Dynamics Panel should initiate planning for a follow-up meeting on Atmospheric Aerodynamics in 1972 or 1973.

(c) An effort should be exerted to plan and finance a coordinated field and laboratory study to obtain data to verify similarity between the wind-tunnel generated flow and the corresponding atmospheric shear flow. In particular, a study of flow over an isolated topographic feature would be useful to test the concept of laminar-flow modeling of meso-scale atmospheric motions.

(d) The Fluid Dynamics Panel should develop closer communication with meteorologists and fluid dynamicists working on micro- and meso-scale motions of the atmosphere. Addition to the Panel of someone active in this field should be considered.

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"The Aerodynamics of Atmospheric Shear Flows"

Topic I – Structure of Atmospheric Shear Flows

1.	Panofsky, H.	*The Structure of Atmospheric Shear Flows.*
2.	Scorer, R.S.	*The Origins and Forms of Dynamic Instability in Clear Air at High Altitude.*
3.	McPherson, A. Nicholls, J.M.	*Mountain Waves in the Stratosphere Measured by an Aircraft over the Western USA During February 1967.*
4.	Barbé, G.D.	*Deux Remarquables Exemples de Cisaillement dans la Stratosphere Concernant le Vent et la Température.*
5.	Gibson, C.H. Williams, R.B.	*Turbulence Structure in the Atmospheric Boundary Layer over the Open Ocean.*
6.	Fichtl, G.H. McVehil, G.E.	*Longitudinal and Lateral Spectra of Turbulence in the Atmospheric Boundary Layer.*
7.	Lettau, H.	*Turbulence Structure in Flow Regimes of Vanishing Mean Shear.*
8.	Hasse, L. et al.	*Determination of Vertical Tranports of Momentum and Heat and Related Spectra of Atmospheric Turbulence in the Maritime Boundary Layer.*
9.	Roth, R.	*Mean Wind-Profile and Turbulence- Considerations of a Simple Model.*
10.	Egger, J.	*On the Development of Cyclones in a Stationary Long-Wave Basic State.*
11.	Zeytounian, R.	*Modèle Aéro (Hydro) Dynamique pour le Calcul du Régime des Ondes de Relief.*

Topic II – Basic Problems Related to Atmospheric Shear Flows

12.	Cermak, J.E. Arya, S.P.S.	*Problems af Atmospheric Shear Flows and Laboratory Simulation.*
13.	Cockrell, D.J. Lee, B.E.	*Methods and Consequences of Atmospheric Boundary Layer Simulation.*
14.	Counihan, J.	*A Method of Simulating a Neutral Atmospheric Boundary Layer in a Wind Tunnel.*
15.	Clark, J.W.	*Laboratory Investigations of Atmospheric Shear Flows Using an Open Water Channel.*
16.	Maull, D.J.	*Wake Characteristics of a Bluff Body in a Shear Flow.*
17.	Coantic, M. et al.	*Etude d'une Soufflerie pour Recherches sur les Echanges d'Energie Atmosphère – Océans.*

18. de Krasinski, J.E.	*On the Use of Diffusion Detector Gases in the Study of Atmospheric Shear Layers with Adverse Pressure Gradients.*
19. Smith, F.B.	*A Review of the Vertical Transfer of Momentum Through the Boundary Layer.*
20. Wippermann, F.	*The Orientation of Vortices due to Instability of the Ekman-Boundary Layer.*
21. Klug, W.	*Diffusion in the Atmospheric Surface Layer: Comparison of Similarity Theory with Observations.*
22. Caldwell, D.R. Van Atta, C.W.	*Some Measurements of Instabilities and Turbulence in Ekman-Boundary Layers.*

Topic III - Industrial Problems Related to Atmospheric Shear Flows

23. Scruton, C.	*A Review of Industrial Problems Related to Atmospheric Shear Flows.*
24. Bearman, P.W.	*Fluctuating Forces on Bluff Bodies in Turbulent Flow.*
25. Johns, D.J.	*Wind Excited Behaviour of Cylindrical Structures – Its Relevance to Aerospace Design.*
26. Albanese, E. et al.	*Statistical Analysis of Gust Velocities for Space Launcher Design.*
27. Valensi, J. Rebont, J.M.	*Aérodynamique des Parois Perforées – Application au Projet d'Ecrans de Protection Contre le Vent – Etude du Fonctionnement.*

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