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WIND FLOW NEAR THE SURFACE OVER NONUNIFORM TERRAIN.(U)
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The OSU/Risø Project is an ongoing study of air flow near the ground over complex terrain. The study combines field observations, data analysis, and theoretical modelling in order to assess and understand the effects of terrain features on the mean flow and turbulence structure in the lower portion of the planetary boundary layer. The method of approach is to choose sites with horizontal scales of less than several hundred meters which have a distinctive inhomogeneity but whose boundary conditions are otherwise relatively simple so that there is some hope of constructing theoretical models, to instrument the site as fully

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as possible to measure the relevant details of the flow, to conduct observations over a long enough period of time to obtain a clear record of the characteristics of the flow, and then to analyze the accumulated data, reconcile the observations with our theoretical constructs, and finally to improve the theory. The types of situations which are being studied are flow over:

1) a change in surface roughness,
2) a change in roughness with an accompanying change in elevation, and
3) a change in surface heat flux.

Other flows which we are presently studying or contemplate future study are:

1) small-scale drainage flows, and
2) flow over an isolated hill.

This work is a joint effort with the Risø National Laboratory, Denmark.

The findings of the project to date have been published in several research papers. The principal results can be summarized as:

1) The wind and turbulence patterns near the ground are influenced by surface inhomogeneities such as terrain form and roughness and heating irregularities. The induced pressure field set up by the intersection of the flow with the surface can have profound effects on wind patterns, including the shapes of vertical profiles of the wind. Theories for flow over irregular terrain must consider the dynamic pressure effects in all but the unrealistically simplest terrains if they are to result in models which simulate the flow patterns faithfully;

2) The presently available "second-order turbulence closure" models for flow over a change in surface roughness reasonably simulate flows with this simple boundary condition providing there is no elevation change accompanying the roughness change.

3) The primary difficulty in modelling flows over complex terrain lies in treating the boundary conditions: the presently used "second-order" equations for turbulent flow are reasonably correct.

A

LIST OF PUBLICATIONS

a. *Published articles, notes and comments resulting directly and indirectly from this project:*

Peterson, E.W., P.A. Taylor, J. Højstrup, N.O. Jensen, L. Kristensen, and E.L. Petersen (1980): Risø 78: Further investigation into the effects of local terrain irregularities on tower-measured wind profiles. *Boundary-Layer Meteor.* (In press.)

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b. Conferences and Symposia:

Peterson, E.W., 1979: The OSU/Risø project. Invited seminar presented at the European Center for Medium-Range Weather Forecasting, Reading, England, May 1979.

Peterson, E.W., N.E. Busch, N.O. Jensen, J. Højstrup, L. Kristensen, and E.L. Petersen, 1978: The effects of local terrain irregularities on the mean wind and turbulence characteristics near the ground. *Paper presented at the WMO Symposium on Boundary Layer Physics Applied to Specific Problems of Air Pollution, Norrköping, Sweden,* 19-23 June 1978, WMO No. 510, 45-50.

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Peterson, E.W., 1976: Observation and analysis of flow over nonuniform terrain. *Preprints 3rd Symp. Atmospheric Turbulence, Diffusion and Air Quality,* Raleigh, Amer. Meteor. Soc., 358-365.

Peterson, E.W., 1976: The wind structure in the surface layer over non-uniform terrain. Invited seminar presented at the Conf. on Army Mesometeorological Res., Las Cruces, September 1976.

Project Summary

A. Introduction

Since 1973, the Department of Atmospheric Sciences at Oregon State University (OSU) and the Meteorology Section, Risø National Laboratory, Denmark have collaborated in a series of field studies and theoretical analyses of micrometeorological flows over complex terrain. For the past six years OSU's contribution to the project has been funded by the U.S. Army Research Office. The major results of the research have been published in several scientific journals and are listed in the List of Publications. Below is a summary of the project, for detailed results the published articles should be consulted.

B. Objective, method of approach, and significance

Theoretical advances in micrometeorology have largely been confined to understanding of ideal, steady-state flows over homogeneous surfaces. Understanding of flows over complex terrain has remained elusive since our ability to model atmospheric flows over complex surfaces has been restricted to those with simple boundary conditions, and we rarely know in sufficient detail the conditions of and affecting real flows near the ground to be able to construct suitable models. The approach we have taken has been to select field sites whose complexity is sufficiently simple that we have some hope of modelling and understanding the flow, to instrument these sites to the best of our resources, to collect data for a sufficient period to be sure we have measured the important aspects of the flow, and to try to integrate and reconcile the observations with our theoretical constructs of the flow situation. So far we have observed flow at a site with a change in surface roughness (Bognaes), a change in roughness with a change in elevation (Risø), a change in heat flux without a change in roughness (Sheermonikoog) and some small-scale drainage flow situations. (The observations at Scheermonikoog were made in Holland in collaboration with the Free University of Amsterdam.) We have published some of our analyses of these flow situations (see List of Publications) but we have only begun to study the large volume of data that has been collected. Particularly we want to study the data taken during the summer of 1978 at the Risø site which as yet has been hardly touched and to test a model of flow over a change in heat flux, which we developed during 1979, on the data obtained at Sheermonikoog. We are also considering participating in a field study of flow over a hill which is being initiated by P.A. Taylor of the Atmospheric Environment Service, Canada. Further field work is being discussed although no definite plans have been made.

Recently there has developed quite an interest in modelling of flows of mesoscale dimensions over complex terrain in order to improve predictive techniques for air pollution problems. We contend, based on our experience, that although it might be possible to develop empirical tools for some specific purposes, it is not really possible to understand these larger scale flows, in which there is interaction between synoptic weather patterns, complicated surface boundaries, and local circulations, before we understand more about the dynamics of much simpler flows, flows of the kind we have been studying in the OSU/Risø project. We therefore believe that the small scale studies which we have been conducting are a necessary support for the mesoscale work that is currently underway and in preparation by other groups.

C. History of OSU-Risø project

The 1958 publication of Elliot's zero-order-closure model for the change-of-roughness problem was followed by more than 20 years of field studies, wind tunnel studies, and the painfully slow development of theoretical models. At the Risø National Laboratory, Denmark (formerly the Danish Atomic Energy Commission's Research Establishment at Risø) is located a 123 m meteorological tower instrumented at 7 levels. High quality data from this site has been collected since 1958. Although these data were not taken for the purpose of measuring flow over a change of surface roughness, some of the wind profiles showed two "kinks" typical of what some would have expected from a double change in surface roughness as the flow passes from the land to the sea and from the sea to the land to reach Risø after traversing Roskilde Fjord (Panofsky and Petersen, 1972). This interpretation appeared to be supported by Elliot's simple model. The roughness lengths computed for the sea surface were extremely small. This was also the case in the Echols and Wagner (1972) study for wind profiles recorded at a tower located on the Texas gulf coast. The roughness lengths for the sea surface seemed much too small since the water surface is not smooth at the wind speeds analyzed in these studies. The shape of these wind profiles could not be reproduced by any of the extant theories. Furthermore, it was not altogether clear whether or not some peculiar kinks which appear in some of these profiles are due to instrument error or orographic effects (Petersen and Taylor, 1973). Subsequent analysis of the Risø tower data (Peterson, 1975) showed that the multiple kinks in the Risø profiles might not actually be induced by a change in surface roughness since they could not be adequately explained by Elliot's simple theory nor by the more complicated first-order closure models (e.g., Taylor, 1969) nor even the second order closure models (e.g., Peterson, 1969a). It was thought that this was because 1) the Risø tower is so located that the fetch from any direction is not really two-dimensional, 2) the terrain elevation varies, and 3) the height of the instruments are such that mesoscale terrain features and baroclinity ought to have pronounced, but at that time unknown, effects on the wind and temperature profiles.

In 1973 it was decided to conduct a joint research program between OSU and Risø to test theoretical models of flow over a change in surface roughness. OSU did not have the facilities to conduct an intensive micrometeorological program of so large a scale and Risø had both experience and facilities in this area. It was concluded that it would be much more economical for OSU to collaborate with Risø than to attempt to develop its own field research facilities. At the beginning of 1974 the micrometeorological field program was begun. The program has been sponsored by the Research Office of the U.S. Army and the Danish Ministry of Trade.

The main purpose of the study was to measure the effects on the wind field of an abrupt change in surface roughness in the direction of the wind to compare these effects with those predicted by theory and to improve the theory. The roughness change which was chosen for this study is that between water and land as it was expected to have a noticeable effect on the flow near the surface. Three 12 m masts were placed roughly in a line stretching from the fjord inland towards the south so that for northerly winds the air would flow from the fjord along the line of masts. The measurements started in October 1974 and data were recorded continuously until September 1975 when the masts were moved to a new site. Most of the data are unsuitable because the wind direction was not perpendicular to the shore, but there were some occasions of strong northerly winds blowing for several hours from the right direction.

1. *Risø Site Description*

The three masts were located on a flat section of the Risø peninsula, sparsely covered with grass of varying height. Actually the site is not quite flat as there is a rise of about 2 m in the first 25 m up from the beach. The site opens to the north on to the Roskilde Fjord; the nearest land northward across the fjord is more than 3 km to the N.N.W. The site is bounded on the east by low trees and bushes, on the west by buildings of about three stories, and on the south by a row of trees lining the roadway. For the change-of-terrain studies the measurements of interest are those taken when the wind was from about 320° clockwise to 20°. The site choice was a compromise between the desire to have a perfectly flat surface with a substantial change in roughness (which is nearly impossible to find in nature) and the need to have a group of competent scientists and technicians at hand to discover and correct malfunctions of the instruments and to monitor the acquisition of the data. Of course a more intensive program of a few days could have been set up at a more nearly ideal site, but then the observation program would have been at the mercy of the weather. If the weather were unsuitable the data would be useless. It was decided that a long-term study at a semi-permanent installation would be more fruitful. The selected site departs from the ideal, i.e., one which would be suitable for the application of two-dimensional change-of-terrain theory, in that there is an uneven rise of ground from the beach, where the first instrumented mast is situated, up to the plateau of the field upon which the other two masts are located. This rise has since proved to have an effect on the flow which is not negligible on the scales in which we are interested. The field is reasonably homogeneous otherwise, and the buildings and bushes on the east and west sides have shown no noticeable effect on the two-dimensionality of the flow.

The measurement system consisted of three climbable masts located roughly on a north-south line. Mast 1 was on the beach, masts 2 and 3 were situated at about 50 and 175 m inland respectively. Each mast had six cup anemometers on arms pointing from the masts toward the north; the anemometers were located at heights of 1,2,3,5,8 and 12 m respectively. Thermometers were located at 0.5 and 12.5 m on each mast. A direct measurement of the temperature difference between the two thermometers on each mast was recorded, as well as the temperature at 12.5 m level. Wind direction was sensed at the top of each mast, at 13 m.

An OSU monostatic acoustic sounder was installed at the met-tower and later replaced by a Risø National Laboratory bistatic sounder.

2. *Research Results, Phase 1*

During the first year (1974), the major concern of this project was technical: getting the instruments, finding the appropriate placement for them, debugging the output, and making necessary corrections. The second year (1975) was mainly occupied by the taking and analyzing of data. During this year a pilot project to test out the feasibility of integrating a sodar with an array of micrometeorological instruments was conducted. This led to one paper on mesoscale phenomenon by Petersen and Jensen (1976).

For the main study, one year of continuous observations were made, and these have yielded many high quality wind profiles for the study of downwind variation. These data were analyzed and reported in Peterson *et al.* (1976). The profiles were found to behave qualitatively in a manner consistent with theoretical second-order closure models (e.g., Peterson, 1969a; Rao *et al.*, 1974). The growth rate of the outer edge of the disturbance appears to be about 1:10 as predicted, but the depth of the substantially modified region of the flow seems greater than expected from model results. The shapes of the downstream mean wind profiles are consistent with second-order closure models. The inflection point and the region of concave-downward curvature predicted by the Peterson model are clearly discernible at masts 2 and 3.

The most intriguing finding of the project at this point is the large effect of the small berm at the beach. The berm affects the pressure field to such an extent that it masks the effect of the change in surface roughness. This has important implications as to our ability to model flows over complex terrain (Peterson *et al.*, (1976). These data were again used to study certain features of the wind profile downwind from a simple escarpment, the berm at Risø (Jensen and Peterson, 1978). Comparisons were made with the several available theoretical models (Taylor and Gent 1974; Frost, Maus, and Fichtl, 1974; and Jackson and Hunt, 1975) for a two-dimensional turbulent boundary layer above isolated low hills.

3. *Bognaes Site Description*

For the 1976 and 1977 programs, in order to assess the magnitude of the effects of the bluff (or berm) on the pressure field by comparison with data from a flatter site, a new location was selected. The Bognaes site is a marshy flat adjacent to the Roskilde Fjord on the Bognaes Peninsula a few kilometers west of Risø. There are several kilometers of over water fetch from the north. The land is so flat that it is often under water during winter storms with northerly flow. The distances of the two inland masts from the coast were 82 meters and 160 meters respectively. Because of the nearly imperceptible slope of the land and the frequent inroads of water, the line of the coast is irregular, making it difficult to say at what point the surface roughness changes. However, this disadvantage is outweighed by the advantage of the flatness of the terrain from water to land and its location near the main support facilities of Risø.

The same instrumentation was used on the masts as was used at the Risø site except that the temperature shields were improved and the variance meters were modified in order to avoid the erroneous values of wind-speed variance that occurred at the Risø site.

The vertical wind profiles, wind direction, temperature, and top to bottom temperature difference were logged continuously in the same manner as described in Peterson *et al.* (1976). During 1977 a telemetering system was used to transmit the rapidly-sampled cup-anemometer signals to Risø during periods when the winds were blowing parallel to the masts. These data allow determination of the cup anemometer variances as well as the mean wind speeds. In addition the longitudinal component of the wind was on these occasions sampled by six hot-wire anemometers placed on the middle mast and transmitted to Risø via the telemetry system. Both the spectra and variance of the longitudinal velocity components were subsequently computed from the hot-wire observations.

4. Research Results, Phase 2

The Risø and Bognaes sites are compared in some detail in Peterson (1976), and the observations are analyzed in Peterson *et al.* (1979). Although the Bognaes site is less than ideal, the observed wind profile development downwind of the change in surface roughness is consistent with theoretical predictions.

5. Risø 1978, Phase 3

During 1978, the previous work on the influence of terrain inhomogeneities was continued and a major, new study was designed to explore the wind flow field in the lowest 20 m above a relatively simple, surface inhomogeneity under the direction of this principal investigator. The measurements themselves were made by personnel from both the Meteorology Section of the Risø National Laboratory and the Department of Meteorology, The Pennsylvania State University.

Three satellite studies were clustered about the main study: 1) an observational study of the diffusion of contaminants over inhomogeneous terrain (this study was carried out simultaneously with the main flow measurement experiment by S.E. Gryning's Risø group); 2) acoustic sounder measurements were made by one PSU group under the direction of Dennis Thompson; and 3) optical phenomena were studied by another PSU group under the direction of Alistair Fraser. John Norman built the drag anemometers and supervised the measurement of the turbulence field.

This principal investigator has collaborated with P.A. Taylor from the Atmospheric Environment Service of Canada on the data analysis for the main study. Taylor has been attempting to model numerically flow over simultaneous changes in roughness and elevation (Taylor, 1978). His results are included in the paper, Peterson *et al.* (1980), to be published in *Boundary-Layer Meteorology.*

"Risø-78" continued the earlier OSU/Risø investigations into the influences of an abrupt change in surface roughness at the same site as the

1974-1975 study. This site exhibits both the water-land roughness change and a change in surface elevation amounting to about 2 m over a horizontal distance of about 25 m. Earlier measurements at this site had shown that the flow was accelerated because of the pressure field which resulted from the elevation change (e.g., Peterson *et al.*, 1976).

The "Risø-78" measurements should yield information about the turbulent structure of the evolving boundary layer in such a situation and, furthermore, should reveal the upstream influence of the elevation change. Profiles of mean wind and temperature, and profiles of turbulence quantities (variances and dissipation) were measured along with fluxes of momentum, temperature and humidity.

A great deal of "state-of-the art" micrometeorological instrumentation was used for this program. Cooperation with the PSU group made it possible for us to get the use of a sufficient number (9) of Norman drag anemometers which can measure all three components of the wind vector. The "Risø-78" instrumentation also included 3 sonic anemometers, thermocouples to measure the heat flux, 6 hot-wire anemometers, 2 Lyman-α humidiometers, 18 cup anemometers, and a number of platinum thermometers and wind vanes. For this instrument array, a total of 72 signals with sampling speeds from 10 to 200 Hz were recorded. Data were recorded as 10 min averaged values. All the raw data are archived at Risø.

Acoustic sounding equipment was used for measurements of velocities above the level of the masts (up to 220 m). Optical experiments were conducted to investigate the temperature profile close to the upstream sea surface.

The OSU/Risø portion of "Risø-78" was partially funded by the U.S. Army, and the initial results from analyzing a small fraction of these data will be published as Peterson, Taylor, Højstrup, Jensen, Kristensen, and Petersen (1980).

6. Change in Heat Flux Study, Scheermonikoog, 1979.

Relatively little experimental work has been published on the influences of a change in heat flux, and most of these have reported on the combined influence of a change of roughness and heat flux (e.g., Rider *et al.*, 1963). An exception is Hsu (1973) in which the internal boundary layer was treated the same as in the free convection regime. A recent study by Vugts and Businger (1977), using data from Scheermonikoog in the Netherlands concentrated on a change in heat flux only. Under the assumptions that the influences of roughness change and change in latent heat flux were unimportant, they studied the change in sensible heat flux and the development of an internal, thermal boundary layer. Unfortunately, Vugts and Businger were unable to measure the fluxes directly becuase of the lack of adequate instrumentation.

The 1979 observation program was an extension of the Vugts and Businger study. It took place on a flat sandy beach on the island of Scheermonikoog which is located off the northern coast of the Netherlands. The previous analysis of data from this site has shown that the roughness change between the sea and the sandy beach has an insignificant influence on the wind profiles and that the site is, therefore, well suited to a study of the adaptation of the flow to a step change in surface heat flux without the other inhomogeneities being important enough to mask this effect.

The following observations were made:

a) Upstream conditions were measured at a mast placed out in the sea. Water and air temperatures were measured as well as wind speed.

b) The developing boundary layer was measured by
   1) four 20 m masts for profile measurements with temperature sensors on all four masts and anemometers on two.
   2) Turbulence measurements using 9 3D-sonic anemometers, a bivane, and a number of hotwire/coldwire systems. (The instruments were placed in horizontal as well as vertical arrays during different phases of the study.)
   3) Humidity measurements were also made using 2 Lyman-α's and a few wet bulb thermocouples.
   4) Additional measurements of surface temperature and radiation were carried out, and an acoustic sounder was placed behind the set-up to track the height of the internal boundary layer.

c) Recording facilities were:
   1) a FSK (frequency shift keying) system with 25 Hz resolution and 16 channels for the turbulence measurements.
   2) A 50 channel recording system with a 1 Hz resolution for the profile measurements.
   3) A mobile digitizing and recording system with 200 Hz resolution and 60 channels for the turbulence measurements and auxiliary recordings.
   4) An Aanderaa recorder for the sea station.

The measurements described above were carried out by Hans Vugts of the Free University of Amsterdam and the Meteorology Section at Risø in collaboration with the OSU/Risø project. The various tasks were assigned as follows:

Tasks a, b(2), b(3) and the acoustic sounder -- the Risø group
Tasks b(1) and the remainder of b(4) -- the Amsterdam group

The Amsterdam group supplied profile and radiative equipment and experience with this site; and the Risø group supplied equipment for the turbulence and sounder measurements as well as its experience with making these types of measurements. Analysis of the data gathered during this study will be conducted by the OSU/Risø project if funds become available.

LIST OF PARTICIPATING SCIENTIFIC PERSONNEL

A) Staff partially supported by this grant

Ernest W. Peterson, Ph.D., Principal Investigator

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*These participants received their "licentiates" (equivalent of Ph.D. in U.S.) at the Technical University in Denmark for work they contributed to this project.

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