J. Fluid Mech. (1984), *vol.* 142, *pp.* 201–216
Printed in Great Britain

Air flow and dispersion in rough terrain: a report on Euromech 173

By J. C. R. HUNT,
DAMTP, Silver Street, Cambridge CB3 9EW

D. P. LALAS†
National Observatory of Athens, Athens, Greece

AND D. N. ASIMAKOPOULOS
Department of Applied Physics, University of Athens, Athens, Greece

(Received 30 November 1983)

Euromech Colloquium 173 was held at Delphi from 13–16 September 1983. Thirty-six participants from eleven countries were present. Papers were presented on: (1) various approaches to calculating and computing air flow in rough terrain in the presence of changes in surface roughness, elevation and temperatures, including methods for interpolating, subject to certain physical constraints, the wind field from measurements at various fixed stations; (2) measurement and satellite photography of air flow in rough terrain near isolated mountains, near coastlines, over mountains, and over mountains near coastlines; (3) the applications of these studies to air-pollution dispersion and the exploitation of wind energy in rough terrain. The discussions led to agreement about how best to use and relate the various techniques for calculating air flows, the role of new techniques in remote sensing for improving understanding of flow in rough terrain, the factors determining air-pollution concentration that need particular study, and the special kinds of information about turbulence needed for estimating wind energy in rough terrain.

1. Introduction

Many studies of air flow near the Earth's surface are directed towards helping with practical problems such as making estimations of air-pollution dispersion, or of the potential for wind-energy conversion systems (WECS) in different sites, or of forces on structures, etc. (See for example the recent book reviewing these applications by Plate 1982.) Because of the practical importance of these air flows and because they are strongly affected by the variations in their kinematical and thermodynamic boundary conditions, i.e. the elevation, roughness (defined by the distribution of small surface obstacles on scales less than 10 m), and temperature of the surface, the study of these air flows has become an active area of research in fluid mechanics as well as microscale and mesoscale meteorology.

There are two other reasons for the importance of this research. The first is that these variations of surface conditions can significantly change the useful characteristics of these air flows (a change that may or may not be beneficial); for example wind-energy potential on a hilltop may be greater than one on a level plain, but air-

† Also Wayne State University, Detroit, Michigan.

pollution concentrations may be worse on the surface of hills. The second reason is that in the most-populated regions of the world the natural variations of surface conditions are particularly marked; most major cities are close to boundaries between land and water, and many cities, particularly those whose air is severely polluted, are close to mountains. Of course the cities themselves also change the surface conditions.

This paper is an account of the presentations and the discussions held at the Euromech Colloquium 173 to discuss current research in air flow over rough complex terrain where there are hills, building, and land–sea temperature differences. An important feature of the colloquium was the discussion about the application of this research to estimating the dispersion of atmospheric pollution and the wind-energy potential in complex terrain.

The colloquium was held in Delphi both because of the interesting research work on these topics under way in Greece to help overcome some acute problems of air pollution and energy shortage in that country, and because the mountains and the sea of Greece provided an ideal setting for a conference on this subject. Byron's words evoke the scene:

The mountains looked on Marathon,
and Marathon looked on the Sea.

The participants at the colloquium were very fortunate to be provided with the hospitality of the European Cultural Centre at Delphi, whose organizing committee were broad-minded enough to consider applied fluid mechanics as part of European culture, a thought that readers of this journal would, we are sure, heartily endorse.

2. Theories of flow over complex terrain

Hunt* (Cambridge) began by discussing some of the different purposes served by models or theories of air flow and dispersion in complex terrain, which ought to affect how they are compared and used.

Specifically, the theory of air flow over hills and mountains ought to be leading to general ideas and estimates for how the broad features of the flow, e.g. locations of maximum and minima of windspeed or direction of the flow, are affected by

(i) different velocity and temperature profiles in the approach flow, which differ considerably between complex and flat terrain, especially in stable conditions (e.g. Hunt *et al.* 1983), and which may be unsteady, as when a sea breeze impinges and perhaps 'splashes' over a mountain:

(ii) grouping of hills;

(iii) the scale over which Coriolis forces must be considered;

(iv) the effect of shape, slope and surface roughness of the hills.

Some examples of these effects were given.

(i) The use of 'triple-deck' theory (Stewartson & Williams 1969) enables turbulent stratified air flow over hills with low slope with rather general upwind profiles to be calculated, including nonlinear effects. As stable stratification increases, it increases the *shear* in the upwind profile; it also increases the buoyancy forces in the flow over the hill. The theory shows how for weak stratification the flow is more affected by the shear than the buoyancy forces, which, as Bradley's (1983) recent field experiments show, leads to an *increase* in the speed up over a hilltop; for stronger stratification the local buoyancy forces dominate, which initially *decrease* the speed-up over the hill. But, at sufficiently large stratification, the speed-up is increased on the lee slope.

* Indicates a speaker at the colloquium. The full title of each paper is given in the references.

(ii) Using the same theory, the air flow over sequences of hills in neutral conditions can be understood by considering the flow in the wake of the one hill as the upwind condition for determining the flow over downward hills.

(iii) Stably stratified flow through a group of hills can be studied by idealizing them (both computationally and in laboratory experiments) as a region of distributed resistance to the incident flow, an analytical technique also being used (less innocently) in the study of underwater vehicles. The horizontal scale over which such a region disturbs the flow direction due to Coriolis acceleration is much larger in very stable conditions (Merkine 1975; Newley, Pearson & Hunt 1984).

(iv) Sea-breeze flows in complex terrain can be idealized as gravity currents (Simpson 1982) flowing in the presence of ambient shear flows and surrounding obstacles.

Craik* (St Andrews University, Scotland) reviewed an important mechanism for inducing secondary flows in inviscid shear flow over an undular surface. Two limiting cases were considered: first when the shear flow is weak relative to the wavy motion, and secondly when the shear flow is relatively strong. The net result of the mean drift motions induced by the wavy motion is to produce a mean displacement of the vorticity of the shear flow, and hence cells of recirculating flow with transverse and vertical velocity components whose vorticity is parallel to the original direction of the shear flow (Leibovich 1983; Craik 1982). This phenomenon is manifested in Langmuir circulation in oceans and lakes, where the surface undulations are caused by surface waves, but it is also likely to occur in the atmosphere when the wind blows over undulating terrain. As with waves, the recirculating flow is forced directly by three-dimensional undulations, but occurs as an instability over two-dimensional undulations. It was suggested that these motions may be significant in the dispersion of pollution.

Tampieri* (Laboratorio Fisbat, Bologna) described some studies of laminar boundary layers with a uniform density gradient flowing over a sequence of two bell-shaped, two-dimensional hills, one hilltop located a distance D downwind of the other. He argued that the key parameters are the upwind buoyancy frequency N, the half-length L of each hill and the wavelength Λ of the lee waves ($\approx 2\pi U/N$, where U is the velocity at height L). From the results of his linear analysis (similar to Sykes 1978; Brighton 1977) for hills with low enough slope that there is no separation, some interesting conclusions could be drawn; for example:

(i) Λ/D is, even for linear analysis, not sufficient to define the broad features of the flows;

(ii) if $NL/U \sim 1$ and $D = 6L$, the largest amplitude of vertical motions occurred downwind of the second hill;

(iii) that if $NL/U > 1.7$, the maximum negative shear stress (which might indicate the onset of separation) is greater on the downwind side of a valley than on the upwind face of a single hill.

Experimental observations, made in a small flume at Cambridge (Brighton 1978), were presented of streamlines over two model hills at low Reynolds numbers (of the order of 300). Tampieri presented a graph of U/NL against D/Λ to show when the flow penetrated into the valley between the hills, an important point for prediction of air pollution episodes. His results were consistent with those of Bell & Thompson (1980). Scorer pointed out that, as well as the Froude number, valley winds in general depend critically on the wind driven by local heating and cooling of the sides of the valley (Scorer 1972, pp. 78–87).

Walmsley,* Taylor & Salmon (Atmospheric Environment Service, Downsview, Ontario) presented a linear model for stably stratified turbulent flow over three-dimensional hills. As in their work on neutrally stratified flow (see Walmsley, Salmon & Taylor 1982; Taylor, Walmsley & Salmon 1983), they have particularly studied the effects on the air flow of the wide range of scales in the shape of any hill, from the overall length of the hill (say 1 km) to small undulations on a scale of less than 10 m. Clearly these require a different analysis! They have shown that it is not possible to explain recent field measurements of wind over hills without considering these small undulations which generalises the approach of Jackson & Hunt (1975). In their new calculations they allowed for the effects of buoyancy forces on the flow above the turbulent inner layer, where it is assumed that the velocity gradients $\mathrm{d}U/\mathrm{d}z$ in the approach flow are small enough to be ignored. For simple shapes of hills their calculations agreed with those of Richards (Hunt, Richards & Brighton 1984).

Bois* (Mécanique Théorique, Paris 6) presented an analysis of linearized atmospheric two-dimensional lee waves over mountains using the equation

$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial z^2}\right)w+S(z)\,w=0$$

for conditions where the 'Scorer' parameter

$$S=\frac{N^2}{U^2}-\frac{\mathrm{d}^2U/\mathrm{d}z^2}{U}$$

decreases from S_0 near the ground to S_{T}, near the tropopause where $z=z_{\mathrm{T}}$, S remaining constant above this height. By using multiple-scale techniques and studying, in general, the turning points of waves where the horizontal wavenumber $k=S^{\frac{1}{2}}$, it was shown that for $z<z_{\mathrm{T}}$ hills induce the familiar stationary system of lee waves, and for $z>z_{\mathrm{T}}$ progressive waves appear which propagate to infinity (where viscous and non-Boussinesq effects are important). Downwind of the mountain the lee waves are reflected along the entire troposphere, and zones exist where none, one, or more lee waves occur (Bois 1982, 1984).

3. Computational models of flow over complex terrain

Sacré* (Centre Technique Scientifique du Bâtiment, Nantes) developed a scheme for computing neutrally stratified turbulent air flow over hills with small slopes whose surface roughness is non-uniform. The turbulent shear stresses are approximated by an eddy viscosity proportional to the turbulent kinetic energy k, which is estimated from a relation of Hinze for shear flows. As in many models, the coordinates are transformed to follow the surface of the hill; since the gradients are large near the hill surface, a non-uniform grid is used, typically 21×32 points over a hill. The model was satisfactorily compared with measurements of flow over hills with uniform roughness, such as those of Bradley (1980). Then it was compared with measurements of flow over roughness changes; it was less satisfactory for flow over rough-to-smooth transition than smooth-to-rough, presumably because the turbulent shear stresses were assumed to be a function of the *local* mean-velocity gradient. The only detailed field experiment, where the roughness and the surface elevation changes, was that performed by Jensen & Peterson (1978) at Risø. This computational model agreed with the analytical models of Jensen & Peterson and Britter, Hunt & Richards (1981), in showing how the roughness change only affects the flow in the inner boundary layer, the elevation changes dominating the flow above this layer. On a hill top, Sacré found that the proportional changes in velocity by the two effects could approximately be calculated as the product of the proportional change of each effect acting on its own (Sacré 1981).

Dalu* (Istituto di Fisica dell'Atmosfera, Rome) used the hydrostatic three-dimensional computational mesoscale model of Mahrer & Pielke (1975) to simulate three different kinds of air flows over the island of Sardinia (about 300×100 km) (Dalu & Cima 1983). The aim of such a model is to show how these different air flows are broadly affected by the mountains (of height 1500 m), the large difference in temperature (10 °C) between the land and the sea, and Coriolis accelerations. It was interesting to see the computations of deviated flow and the strong down-draughts in the lee of the mountain during the dry, cold Mistral wind from the northwest, and the rotating horizontal converging flow in the centre of the island during a sea-breeze flow. There is little interaction between such low-level, thermally driven flows and the approach wind when it is a warm Scirocco from the southeast. The computational grid is 20 km square and its lowest height resolution is 50 m above the surface. Since it has only been compared with the radiosonde observations at one location, the computations have not yet been properly verified. Scorer showed some of his photographs from satellites of clouds formed by high- and low-level lee waves over Sardinia's mountains, which could provide a check for these kinds of computations.

Lalas* (National Observatory, Athens) introduced the general topic of estimating the wind field over a wide region in order to assess the potential for exploiting wind energy. The kinds of data required about the wind are the statistics of the mean value and direction of hourly mean values, the persistence of the wind, the statistics of gusts and the wind profile above the ground. There are two different general approaches to estimating these wind fields, one being to interpolate between ground level wind measurements or to extrapolate downwards from measurements of the geostrophic wind by radiosondes. The second approach is to compute the flow from some upwind boundary conditions using, for example, mesoscale models based on the equations of motion. The latter generally needs an enormous quantity of computer time.

In fact there are a variety of methods between these two extremes, which combine some interpolation and some information or equations derived from the continuity and dynamical equations. Lalas himself used the NOABL model developed by Science Applications Incorporated (see Phillips*). It was developed from the 'Mathew' model of Sherman (1978), in which the mean flow field is interpolated from the horizontal components of wind at various stations, subject to the constraints of satisfying the continuity equation and the need for the low-level flow to pass *over* hills in neutral conditions and around hills in stable conditions. (This was the kind of model used to estimate the dispersion of the after effects of the accident in 1979 at the Three Mile Island nuclear power station in Pennsylvania.)

In this case the model was used to estimate the wind field over the mountainous island of Crete (50 km wide and 250 km long), using a 5×5 km horizontal grid with 40×60 points, and 15 levels in the vertical ranging from 50 to 500 m in spacing. The wind was interpolated from four ground stations and vertical sounding from a radiosonde. As one would expect, northerly winds produced high velocities where the wind funnelled through the passes and around the sides of the mountains. The model was tested by comparing estimates of the wind at several ground stations on the basis of wind measured at only one other station. The reasonably good agreement suggested that long-term statistics of the wind at ground level could be obtained by extrapolating from the known statistics of the geostrophic wind.

Scorer questioned whether all this elaborate measurement and computation was really necessary, since the windiest places can be readily identified from looking at stunted vegetation or areas of soil erosion. Lalas replied that these complex investigations are necessary because current wind-energy converters have characteristics (and economics) that are quite sensitive to the wind structure and wind statistics.

Phillips* (Science Applications Inc., La Jolla, California) also discussed these two different approaches to calculating the wind field, developed as part of the U.S. Department of Energy programme for finding suitable sites for wind-energy systems; namely interpolation between measurement stations guided by 'simple physics' (the NOABL model) and computations based on equations of motions with eddy-viscosity models for the turbulent shear stresses, and the hydrostatic approximation for vertical pressure gradients (SIGMET model). The former approach tends to be used to indicate suitable areas, while the latter, more-expensive, method is used to investigate particular sites in some detail. Examples were given of three sites on Oahu (Hawaii), Nevada and Gotland Island (Sweden). The finest horizontal grid used was 200 m; typically grids of $25 \times 35 \times 10$ points are used for computations which take 30 s on a CDC7600. Given the observed upwind boundary conditions, the calculated air flow agreed 'reasonably' well with downwind measurement. (A more stringent test would be to compare the *changes* in the calculations with the *changes* in the observed flow.) There was a tendency to overpredict thermal effects and underpredict orographic effects. No effects of clouds or heating by rain were included. A number of questioners suggested that such computations needed to be checked against a range of analytical results to test both the physical assumptions and the numerical methods of the model. Dr Phillips said that such tests were routinely prepared but seldom published, which many thought was unfortunate.

Moussiopoulos*, Gassmann, Haschke & Pandolfo (University of Karlsruhe, Swiss Federal Institute for Reactor Research, Center for the Environment and Man (Hartford, USA)) showed how it is possible to compute equations coupling the distributions of wind, temperature, water vapour and pollutants using grids over areas of the order of 50 km square. With horizontal grid scales of about 3–15 km and time steps of 0.5–5 min, the model took 5 hours to adjust to given fixed conditions. Local eddy diffusivities are assumed and vertical accelerations are neglected. The model has been used to predict the effects of groups of large cooling towers in the upper Rhine valley, and is being used to estimate the formation and dispersion of particulate and gaseous pollution in the Athens basin (see Moussiopoulos *et al.* 1983). A question was raised about applying upwind-differencing methods for simulation over 12 hour periods because of the high level of numerical diffusion to be expected. The author pointed out that the fine vertical resolution of the grid near the ground (and below it) enabled calculations to be made of ana- and katabatic air flows on the sides of the hills and valleys. These air flows, often less than 100 m in depth, are of great importance in ventilating a valley.

Bergeles* & Athanassiades (National Technical University, Athens) are computing the flow over a single rounded hill in a turbulent boundary layer. The equations are expanded in finite-difference form in an orthogonal curvilinear coordinate system with the shear stresses represented by an isotropic eddy viscosity K, which is estimated from two further equations for the turbulent kinetic energy per unit mass k and rate of dissipation of turbulent kinetic energy per unit mass ϵ: $K \sim k^2/\epsilon$ (the 'k-ϵ' model). The momentum equations are solved iteratively by assuming the flow field, then calculating the pressure; then correcting the flow field etc.: the 'TEACH' code was used as developed at Imperial College. The computations were performed on a 40×15 grid extending over 26 hill heights H in the horizontal and 10 hill heights in the vertical for a hill with 'half-lengths' L equal to 8, 5 and 3 times H. The boundary-layer thickness was assumed to be $8H$. The computations were compared with wind-tunnel experiments by Khurshudyan, Snyder & Nekrasov (1981), and showed general agreement for the *mean flow*, and to some extent even in the separated region of the flow. Questioners commented that much of the computation may be wasted because, except close to the surface and in the separated flow region, the mean flow is controlled by the inertia and vorticity of the incident flow and is independent of shear stresses (which, in the separated-flow region, are poorly represented by the k-ϵ formulation). Bergeles finds that it is simplest to compute the shear stresses even if they have no effect on the mean flow. He also suggested that more complex models for stress are appropriate for separated flows. Another questioner wondered about Görtler vortices on the slopes of hills; Bergeles said that they are not included explicitly in the model and have not been observed in turbulent-flow experiments.

4. New observations and measurements

Scorer* (Imperial College, London) showed what a wide range of atmospheric phenomena can be studied from high-quality black-and-white satellite photographs in the visible and infrared radiation wave band (Scorer 1984). The main features of such photographs are clouds, haze and fog in the atmosphere, the coastline, mountains and snow cover on the land and reflection of light off the sea (sea glint) and sea temperature. From the angle and elevation of the sun, the depth of cloud formations could be inferred; from the sea glint, variations in wind speed over the sea could be deduced.

Downwind of mountain barriers, the photographs showed how high-level air rises to form extensive arches of cirrus cloud while lee-wave clouds of wavelength around 12 km are common in the middle- and low-level flows. Some cirrus extends hundreds of kilometres downwind. It was striking how regular the lee-wave clouds were even over irregular terrain. Examples were shown from Greenland to the Carpathians and Norway to Gibraltar. The Mediterranean Sea is surrounded by mountains with gaps; the strong airflow through these gaps as it passes over the sea, roughens it and affects the 'sea glint'. (Calm sea is very bright when the sun is reflected in it, but is *darker* than rough seas when there is no direct reflection.) The development of sea fog, and haze in mountain valleys or plains surrounded by mountains which affect air pollution can be studied rather well from these photographs. The anabatic flows up the slopes of hills and valleys induce the formation of cumulus clouds; these are also formed by sea breezes near the coast. The diurnal development of these effects can be studied from photographs taken each time the satellite passes. Many delegates from several European countries had never seen such well-defined photographs before and felt that they should be able to improve their understanding and test their models for various kinds of airflow and air pollution dispersion.

Beljaars* (Royal Netherlands Meteorological Institute, De Bilt) has been studying the flow in the surface layer (less than 50 m) of the atmosphere where the terrain is not uniform and various kinds of obstacles are scattered around (Beljaars 1982; Beljaars, Schotanus & Nieuwstadt 1983). He presented some new measurements of mean wind profiles at the Cabauw tower in the Netherlands, which is surrounded by meadows, trees and small ditches; a terrain with a typical roughness length z_0 of 3 cm. He particularly commented on the velocity profiles (20 or 30 heights) downwind of a line of distributed resistance that is porous to airflow such as a hedge. When plotted against the logarithm of the height z, the profiles displayed the well-known forms of two straight lines with the change in slope at about the top of the internal boundary layer (or wake). This was found to have the same height as that over a roughness change and agreed with Townsend's (1965) theory. An interesting feature of these experiments were the measurements of the variances σ_u^2 and σ_w^2 of the horizontal and vertical velocity fluctuations and the Reynolds stresses $\overline{uw}$. It was found that the vertical turbulence was proportional to the local value of Reynolds stress above and below the internal boundary layer, but the horizontal turbulence did not adjust quickly to the local flow within the internal boundary layer. This was found to be consistent with the other observation that the Reynolds stresses can only be computed from the mean velocity gradient *above* the disturbed inner layer. These results about the adjustment of turbulence in non-homogeneous terrain are consistent with the ideas recently put forward by Panofsky *et al.* (1981).

Smedman* (Uppsala) described an analysis of measurements of the mean and fluctuating velocity profiles at a potential wind-energy site near woods and near an indented part of the Baltic coastline. The site is sloping and there are large roughness changes between the sea and the land where, depending on the direction, there existed both open fields and woods. By assuming that the effects on the air flow of changes in the surface roughness and elevation could be superposed (cf. Sacré*), it was possible to give a quantitative explanation for some of the differences between the observed mean velocity profiles and the usual logarithmic profile found over level terrain in neutral conditions. The measurements of turbulence provided further evidence of how the low-frequency component of the turbulence spectra take longer to adjust than the mean flow or the components that contribute most to the Reynolds stress. The fact that the low-frequency components are not closely related to the *local* mean and variance needs to be recognized in choosing sites for exploiting wind energy (Panofsky *et al.* 1981). In this case it meant that there was less low-frequency energy than expected for flat terrain when the wind came off the sea.

Pretel* & Zelený (Acad. Sci. Prague) made comparisons between field measurements near the surface over flat terrain at Tsimlyansk (U.S.S.R.) and on an 80 m tower in hilly terrain at Kopisty (Czechoslovakia), a region where there is considerable air pollution. The tower was about 5 km from a ridge 700 m high; there were also smaller hills, buildings and trees nearby on scales of 50, 10, 5 m. The roughness length was approximately 1–2 m. The most interesting comparison was of the tubular intensity σ_u/U as a function of the wind speed in slightly unstable (i.e. convective) conditions; over level terrain this intensity slowly increases as the mean wind speed U decreased below 6 m s^{-1}, whereas in hilly terrain it is increased much more markedly (suggesting that convective activity is much enhanced). It was found that the ratio of the standard deviation of the vertical component to the surface friction velocity σ_w/u_*, was less near hills and was less sensitive to stratification than over level terrain. Interpretation of such data taken at one position in complex terrain is very difficult.

Deligiorgi, Lalas,* Asimakopoulos & Helmis (Athens) described some unusual measurements of the air flow and temperature structure over a 1000 m mountain (Hymmetus) near Athens where sea breezes arrive from two directions. They used a fixed turbulence probe as well as standard meteorological instruments and a conventional bistatic acoustic sounder (Helmis, Asimakopoulos & Cole 1983), a specially developed high-resolution monostatic acoustic sounder (Cole *et al.* 1980), and a tethered balloon to measure temperature. Two days were picked out for special attention, one with a strong sea breeze from the SW opposing a northerly air flow, and the other with a passing cold front. The measurements showed that there was a convective layer of the order of 1200 m deep with a weak inversion within it at 200 m. Thermals that were generated on or upwind of the mountains and passed over it, as shown by the acoustic sounder. During the passage of the sea breeze, large downward vertical velocities were observed (*ca.* 1.8 m s^{-1}). When the weak cold front arrived, it behaved like a wave rising twice to the mountain top before finally sinking below it. A strong acoustic sounder echo, which appears suddenly, may have been caused by turbulence generated within the front by the large local variations in the wind *direction.*

Analysis of the velocity spectra showed that they were similar to those measured over level terrain; the same was not true for the temperature and refractive index spectra, which showed less variance at high frequencies. Such information is of importance for communications through the atmosphere over mountainous terrain. As was pointed out these measurements raise many questions, for example, how does a sea breeze, normally about 300 m deep, rise to 1000 m ? how does it interact with anabatic winds up the mountain; how does it interact with a sea breeze coming the other way? (Such a situation on level terrain was studied by Simpson & Rider 1968).

Hogstrom,* Alexanderson & Bergstrom (Uppsala, Sweden) described a novel analysis of measurements of mean wind speed and direction from a 145 m mast using pilot balloons, turbulence measurements and radiosonde ascents near the coast at the tip of the island of Gotland in the Baltic Sea. During a two-day period of a very steady warm (20 °C) air flow from the SE over the cold (6 °C) sea, large variations in the direction and magnitude of the mean surface wind, i.e. the wind hodograph, were observed. A polar plot of the wind vector for various times (the hodograph) was quite unusual. Two mechanisms were suggested; one being the diurnal variation in the island's resistance to the flow caused by the variation in its surface temperature, which may induce some flow to pass round the tip of the island during the day while allowing it to flow over the island at night. The other was the effect, 200 km upwind, of the daytime flow off the warm Latvian coast speeding up and rotating as it passes over the cold Baltic Sea – a developing effect which could produce a jet flow at night over the island. It was suggested that these novel but important mechanisms might be found quite widely near coastlines.

Bouquet* (Poitiers) presented the methods of wind-tunnel studies of the air flow round mountainous terrain, with particular reference to a study at 1/1250 of the island of Madeira. The purpose of the study was to find out the effects of these flows on aircraft approaching and landing at a projected airport. Therefore the aspects of the air flow to be investigated were not statistics of the mean flow or turbulence, but rather the nature of the large coherent gusts or vortices that are shed off the mountain; in particular whether these are strong enough and persistent enough to be dangerous to aircraft. It is interesting that the best way to answer this question appears still to be measurements of deflections of model aircraft on simulated flight paths and the use of lots of smoke flow visualization, rather than by many detailed flow measurements.

An important conclusion was that for downwind in the wakes of mountains (in this case 2 km away from 300 m mountains) the vortices are strong enough to be of concern; note that these vortices are unsteady but have a coherent structure. It was interesting to note that (cf. Jenkins *et al.* 1981) the directions of these were *opposite* to those of 'horseshoe' vortices.

Antoniou, Bergeles* & Athanassiades (National Technical University, Athens) have been measuring the mean flow downwind of surface-mounted rectangular prisms in a 40×23 cm wind tunnel in order to understand how the length L_R of the recirculating region varies with the width w and the height $h(=2$ cm) of the prism and how the boundary-layer flow recovers in the wake downwind. The thickness of the approaching turbulent boundary layer is about $\frac{2}{3}h$ and the Reynolds number based on h is about 2×10^3. As other authors have found, the length L_R of the recirculating wake decreases linearly with the width w when the width (in the flow direction) is not long enough for the flow to attach on the top surface of the obstacle; the attachment also speeds up the rate at which the wake flow develops into a boundary layer. Following Bradshaw & Wong (1972), Clauser plots are a useful way of representing this recovery process.

Kotsovinos* (Xanthi, Greece) began by reminding us all that flow-visualization experiments can be used as much for education of the public and administrators as for scientific investigation, and how important this is if research into air-pollution dispersion is to help with the formulation of appropriate policies for air-pollution control. Kotsovinos was interested in dispersion of buoyant chimney plumes in stratified stable conditions on a narrow plain bounded by the coast and by mountains. In very still conditions the motion in these plumes might be larger than in the natural airflow; then the pollutants move at a rate depending sensitively on the entrainment rates into the plume, the speed of the front of the chimney plume where it levels out, and how it interacts with mountains. It was suggested that this process could be modelled most effectively by distorting the horizontal and vertical scales, as, for example, by steepening the mountains. The results of such experiments looked very dramatic, but a number of questioners wondered how reliably they could be extrapolated to full scale.

5. Air-pollution dispersion

Callander, Jenkins, Maryon* & Whitelock (Meteorological Office, Bracknell) and their colleagues have been measuring the mean and turbulent velocity distribution and also the dispersion of gases released from small sources, mainly in neutral conditions, in hilly terrain in ridges and valleys in South Wales and on isolated hills (Blashaval) in the Hebrides. Maryon described a particular experiment at Blashaval where tracer gas was released from a source 8 m high on the upwind face of a hill whose height is 100 m and maximum slope about 1/5 (Maryon & Whitlock 1983). Dosage samplers attached to a frame 12.5×15 m high were used to measure time-integrated concentrations at 100 m downwind of the source. Despite the relatively low slope (which might be expected to increase the wind speed by about 70%) the dispersion of the tracer was significantly different from that over level ground. The reasons are that the mean flow and the low-frequency, large-scale horizontal flow diverges over the hill; also the convergence of the streamlines and the increased shear stress amplify the lateral component of turbulence σ_v by about 60%. The vertical profile of mean concentration had its maximum value close to the surface rather than at a height a little less than the source height. This was ascribed to the converging of the streamlines on the upwind slope, but, when a simple estimate for the rate of convergence had been introduced into the random-walk model of Ley (1982), the calculation did not reproduce the full extent of the depression of the maximum. Thus the trends of the results were understandable, but it appears that the calculations of dispersion over a hill are at the moment less reliable than those of wind speed.

Petrakis & Lalas* (National Observatory, Athens) described the typical air flow in the Athens basin found on occasions of the worst air pollution episodes (see Lalas *et al.* 1983). The sources of the air pollutants are: for sulphur dioxide, largely industry; for particulates, industry and traffic; for nitrogen oxides and hydrocarbons, largely traffic. It is important to know the diurnal variation of the air flow and how pollutants are dispersed in conditions where the geostrophic wind is weak so that sea breezes generate most of the air movement.

Data from local stations during sea-breeze days revealed a highly repeatable pattern of the diurnal variation of the wind speed and direction in the basin (10×30 km). A sea breeze front is found to move NNE up the basin, and simultaneously a second one is formed on the Mesogia plain to the east of Mount Hymmetus, which is a NS ridge. These two fronts interact both at the mountain and at the northern end of the ridge. There is no evidence of a flow from another basin to the SW (Eleusis), which could transport pollutants directly from the refineries located there to the main basin.

An interpolative numerical model (NOABL; cf. Lalas*) was used to calculate the flow field for various days starting from the data of the ground stations and incorporating available upper air soundings. The effect of the high mountains on the air flow is incorporated into the interpolation (but on the basis of steady-flow calculations in an unsteady situation). Utilizing the calculated flow field, a trajectory of an air parcel released at 0600 h in the centre of the city was obtained. Generally such a parcel is found to be transported first to the shoreline or beyond and then advected back north, past the point of release. It is almost out of the basin by 1100 h. It becomes clear then that such air-parcel motions should be given serious attention in any anti-pollution strategy to be used in Athens. Some of the more obvious policies can be shown to be ineffectual. These direct measurements of air-flow pollutants agree with motions inferred from the diurnal variation of concentration of pollutants, especially the high concentration of ozone at the shoreline (which sometimes exceed the Californian ozone standards).

6. General discussions and reviews

6.1. *Air-pollution dispersion*

Skiotis* (Greek Government Environmental Protection Agency, PERPA) reiterated the need for reliable methods of forecasting air-flow trajectories in order to develop an air-pollution control strategy which emphasizes emission curtailment; such an analysis is an essential part of the diagnosis and must precede the prescription of a cure. However, in discussion it was pointed out that trajectories are not sufficient; there are many other important but unanswered questions, for example: what happens to ozone and other pollutants during the night; is there any significant mixing with unpolluted air? It is observed that ozone does not increase during an episode, whereas nitrogen oxides and haze accumulate. How can the significant effects of haze on the heat balance be estimated? Can simple predictions be improved for deciding which synoptic conditions are likely to produce air pollution episodes? More generally it was recognized that complex terrain and sea breezes have strong effects on the dispersion of air pollutants and that there need to be careful field experiments with *inert* tracer gases before the intricacies of the dispersion of reacting gases in complex terrain can be understood.

6.2. *Wind energy*

Tassiou* (Public Power Corporation, Athens) presented some statistics about the oil savings and the capital costs involved in a programme of introducing wind-energy systems to provide 20 % of the electrical energy of the islands of Greece; a programme that is just about economical at the moment. In planning such a programme, it is necessary to estimate the hourly wind statistics (cf. Lalas*) at many different locations near coastlines and mountains.

In addition to these statistics at one height (say 10 m) it is important to estimate the mean velocity gradient and gusts because of their effects on the fluctuating loads on a rotor, and on the available wind energy. There have been a few incidents of mechanical failure caused by these effects. Consequently one needs to be able to predict both the general features of the flow over 10–20 km, and the vertical distribution over 50 m. There was some discussion about the wide range of approaches to this problem ranging from reliance on more or less complex observation and measurement, perhaps using remote sensing, to mathematical models which were more or less interpolative. It was emphasized that the important features of the air flow required for wind-energy studies are different from those of importance in other studies, for example the low-frequency components of importance are those parallel to the mean wind, whereas in air pollution studies it is the perpendicular components. It is also striking how few systematic laboratory experiments have been performed on the flow over groups of hills, as opposed to *ad hoc* experiments in particular topography.

6.3. *Air flow over complex terrain*

Walmsley* introduced this discussion and followed Orlanski (1975) in considering scales first of 200 m to 2 km (micro α-scale) then 2–20 km (meso γ-scale) and finally 20 km to 200 km (meso β-scale). He concentrated on air flow over hills and mountains. Much recent work has been concentrated on the micro α-scale with analytical methods, finite-difference and finite-element computations and many field and laboratory studies. Some research is aimed at providing computational or modelling techniques, but other research is leading to useful 'rules of thumb' for wide application. There does not seem much evidence that very complex models are much better than quite simple models. The understanding of flows in the separated region is still very limited.

In the meso γ-range, one is usually interested in the flow over groups of hills. Some simplification is necessary to analyse or compute the flow in this range: computers are not large enough and the models of turbulence are not good enough simply to extend the micro α-scale computations. Appropriate simplifications may become possible when field experiments extend to this range. (The advances in remote sensing should enable a new generation of such field experiments to be performed more easily than has been possible in the α-range field experiments. But it is important that something of the same care be accorded to γ-range field experiments that has been a hallmark of the recent α-range field experiments in North America and Europe.)

For the meso β-range (Lalas had reviewed the models in his paper) it was reiterated that the computations based on equations of motion ought to be tested wherever possible with exact solutions, and the comparisons published. There needs to be careful thought about how best to integrate interpolation and constraints based either on 'simple physics' or on local solutions of equations. (The same problems are being actively explored by oceanographers; Wunsch & Minster 1982.)

One of the important features of flow over hills brought out in recent field experiments is that in stable conditions, say in each 20 min period, the upwind velocity and temperature gradient may be quite different to that in the succeeding periods, and the nature of the flow over the hill may be quite different, e.g. passing over it or around it. Consequently the flow over the hill averaged over one hour could not be the result of the upwind conditions averaged over one hour. Such an assumption is commonly made when comparing the computations and field measurements, especially over γ- and β-ranges. (The modelling of turbulence is irrelevant to this problem).

Hogstrom* introduced a general discussion on sea breezes, and pointed out some important, but common, complex features of these flows which are poorly understood; their interaction with existing winds caused by synoptic forcing: their tendency to form low-level jets and inertial waves caused by variations in sea-surface temperature off the coast (e.g. California) or by frictional decoupling; the structure of the internal boundary layer at the coast, especially where the coastline is highly indented. In the latter situation the air over the sea between land tends to sink and any island in the sea may experience fumigation from elevated sources of pollution on the land. An important implication of low-level jets is that their energy may be advantageous to wind mills but their large velocity gradients dU/dz may lead to damaging loads on the blades.

7. Conclusions

There were seven main points arising from the meeting.

1. The different approaches to analysing and computing flows in complex terrain can complement each other and ought to be tested against each other as well as against field data. For example, any improved understanding of the relation between flow over a hill and its upwind conditions can be used to improve interpolation schemes for computing air flow, or conversely the upwind conditions for flow over a particular hill might well be determined by a large-scale finite-difference model for a whole region.

2. There is a need for laboratory modelling, field measurements and computation for flow over rough terrain over the scale 2–20 km.

3. The current evidence is that it is not necessarily beneficial to use ever more complex models as the terrain becomes more complex. Simplifications are necessary.

4. New techniques for remote sensing from satellite photography, acoustic sounders, and radar are beginning to provide valuable insights and quantitative information about the flow of air, water vapour, and pollutants in complex terrain, particularly in understanding the relation between local and synoptic scale air flows. These are important for predicting episodes of high pollution concentrations or high local winds.

5. The dispersion of air pollutants from their sources over a regional scale and the formation of secondary pollutants is sensitive to the vertical mixing processes and the trajectories of air flow at different levels. These mechanisms are not well understood over flat or rough terrain.

6. Whenever low-frequency or large-scale turbulent eddies need to be predicted, it is important to remember that they are not in general determined by local conditions, because they have a much larger relaxation time than the small-scale turbulence or even than the mean flow.

7. As one should have expected, our visit to the oracle at Delphi did not provide unambiguous answers to our questions.

We are grateful to Dr Walmsley for showing us a copy of his own report on the Colloquium.

REFERENCES

(* denotes a paper given at the colloquium)

ANTONIO, J., BERGELES, G. & ATHANASSIADES, N.* Flow development behind surface mounted obstacles.

BELJAARS, A. C. M.* Some properties of the non-homogeneous surface layer.

BELJAARS, A. C. M. 1982 The derivation of fluxes from profiles in perturbed areas. *Boundary-Layer Met.* **24**, 35–55.

BELJAARS, A. C. M., SCHOTANUS, P. & NIEUWSTADT, F. T. M. 1983 Surface layer similarity under non-uniform fetch conditions. *J. Climate Appl. Met.* (to appear).

BELL, R. C. & THOMPSON, R. O. R. Y. 1980 Valley ventilation by cross winds. *J. Fluid Mech.* **96**, 757–767.

BERGELES, G. & ATHANASSIADES, N.* Computation of the flow over a two-dimensional hill.

BOIS, P. A.* Asymptotic modelization of lee waves by confined flows.

BOIS, P. A. 1982 Rôle de la viscosité dans les ordes de relief. *C. R. Acad. Sci. Paris* **294**, II, 823–825.

BOIS, P. A. 1984 Asymptotic theory of Boussinesq waves in the atmosphere. *Proc. Course 'Models for Atmospheric Flows', Centre International des Sciences Mécaniques, Udine.*

BOUQUET, R.* Wind tunnel study of the wind field structure around an airport.

BRADSHAW, P. & WONG, F. Y. F. 1972 The reattachment and relaxation of a turbulent shear layer. *J. Fluid Mech.* **52**, 113–135.

BRADLEY, E. F. 1980 An experimental study of the profile of wind speed, shearing stress and turbulence at the crest of a large hill. *Q. J. R. Met. Soc.* **106**, 101.

BRADLEY, E. F. 1983 Stable and unstable airflow over a small escarpment. In *Proc. 6th Wind Engng Conf., Brisbane.*

BRIGHTON, P. W. M. 1977 Boundary layer and stratified flow over obstacles. Ph.D. Dissertation, University of Cambridge.

BRIGHTON, P. W. M. 1978 Strongly stratified flow past three-dimensional obstacles and mesoscale vortex sheets in the atmosphere. *Q. J. R. Met. Soc.* **104**, 289.

BRITTER, R. E., HUNT, J. C. R. & RICHARDS, K. J. 1981 Analysis and wind-tunnel studies of speed up, roughness effects and turbulence over a two-dimensional hill. *Q. J. R. Met. Soc.* **107**, 91.

CALLANDER, B. A., JENKINS, G. J., MARYON, R. H. & WHITLOCK, J. B. G.* Short range dispersion experiments made in hilly terrain.

COLE, R. S., ASIMAKOPOULOS, D. N., MOULSLY, T. J., CAUGHEY, S. J. & CREASE, B. A. 1980 Some aspects of the constriction and use of atmospheric acoustic sounders. *Radio & Electronic Engr* **50**, 585–597.

CRAIK, A. D. D.* A laminar mixing mechanism for the air flow over undular terrain.

CRAIK, A. D. D. 1982 Wave-induced longitudinal vortex instability in shear flows. *J. Fluid Mech.* **125**, 37–52.

DALU, G. A.* Modelling of air flow over Sardinia.

DALU, G. A. & CIMA, A. 1983 Three-dimensional air flow over Sardinia. *Nuovo Cim.* **6**, 6288–6308.

DELIGIORGI, D., LALAS, D. P., ASIMAKOPOULOS, D. N. & HELMIS, C. G.* The structure of the atmospheric boundary layer over a steep hill.

HELMIS, C., ASIMAKOPOULOS, D. N. & COLE, R. S. 1984 A low-level atmospheric vertical velocity comparison between a high resolution acoustic sounder and turbulence probe. *IEEE Trans. Geosci. & Remote Sensing* (to appear).

HOGSTROM, U., ALEXANDERSSON, H. & BERGSTROM, H.* A case study of a boundary layer and regime in stably stratified air observed at the island of Gotland in the Baltic Sea.

HUNT, J. C. R.* Air flow and dispersion among groups of hills and in sea breezes.

HUNT, J. C. R., KAIMAL, J. C., KAYNOR, J. & KORREL, A. 1983 Observations of turbulence structure in stable layers at the Boulder Atmospheric Observatory. *NOAA Environ. Res. Lab. Rep., Boulder, Colorado.*

Hunt, J. C. R., Richards, K. J. & Brighton, P. W. M. 1984 Turbulent stratified flow over hills with low slope. Submitted to *Q. J. R. Met. Soc.*

Jackson, P. S. & Hunt, J. C. R. 1975 Turbulent wind flow over low hills. *Q. J. R. Met. Soc.* **101**, 929.

Jenkins, G. J., Mason P. J., Moore, W. H. & Sykes, R. I. 1981 Measurements of the flow structure around Ailsa Craig, a steep 3-dimensional isolated hill. *Q. J. R. Met. Soc.* **197**, 833–852.

Jensen, N. O. & Peterson, E. W. 1978 On the escarpment wind profile. *Q. J. R. Met. Soc.* **104**, 719.

Khurshudyan, W. W., Snyder, W. H. & Nekrasov, J. 1981 Air flow and diffusion of pollution over two-dimensional hills. *Environ. Prot. Agency, Rep. Res. Tri. Park, NC* EPA-600-4-81-967.

Lalas, D. P.* Modelling of the flow over Crete for wind energy estimation.

Lalas, D. P., Asimakopoulos, D. N., Deligiorgi, D. G. & Helmis, C. G. 1983 Sea breeze circulation and photochemical pollution in Athens, Greece. *Atmos. Environ.* **17**, 1621.

Leibovich, S. 1983 The form and dynamics of Langmuir circulation. *Ann. Rev. Fluid Mech.* **15**, 391–427.

Ley, A. 1982 A random walk simulation of two-dimensional turbulent diffusion in the neutral surface layer. *Atmos. Environ.* **16**, 2799.

Mahrer, Y. & Pielke, R. A. 1975 Numerical study of the air flow over mountains using two-dimensional version of the University of Virginia mesoscale model. *J. Atmos. Sci.* **32**, 2144.

Maryon, R. H. & Whitlock, J. B. G. 1984 Short-range dispersion experiments on the windward slope of Blashaval, North Uist. Meteorological Office. *Met.* O 14 *Internal Memo.* TDN 150.

Merkine, L. O. 1975 Steady finite-amplitude baroclinic flow over long topography in a rotating stratified atmosphere. *J. Atmos. Sci.* **32**, 1887.

Moussipoulos, N., Grassmann, F., Haschke, D., & Pandolfo, J. P.* Development of a numerical model for simulations of air pollution episodes in Athens, Greece.

Newley, T. J., Pearson, H. J. & Hunt, J. C. R. 1984 Stably stratified rotating flow through groups of obstacles (to be submitted for publication).

Orlanski, I. 1975 A rational subdivision of scales of atmospheric processes. *Bull. Am. Met. Soc.* **56**, 527–530.

Plate, E. J. 1982 *Engineering Meteorology.* Elsevier.

Panofsky, H. A., Larko, D., Lipschutz, R., Stone, G., Bradley, E. F., Bowen, A. J. & Højstrup, J. 1982 Spectra of velocity of components over complex terrain. *Q. J. R. Met. Soc.* **108**, 215.

Petrakis, M. & Lalas, D. P.* Air flow in the Athens basin.

Phillips, G. T.* Wind energy siting methodology and SIGMET model verification studies.

Pretel, J. 1984 Zur Beschreibung der Terraininhomogenität in der Bodenschicht der Atmosphäre. *Z. Met.* **34**, Hft 4.

Pretel, J., Zelený, J. & Křížek, P. 1984 Verwendung der Ergebnisse der MESP-81 zu weiteren Untersuchungen der Bodenschicht der Atmosphäre über gegliederten Gelanden. *Geod. Geophys. Veröff. R. II der NKGG, Berlin.*

Pretel, J. & Zelený, J.* Effects of non-homogeneous terrain and roughness on turbulence in the surface boundary layer.

Sacré, C.* Simulation of the simultaneous effect of roughness and two-dimensional topography on wind speed for wind energy applications.

Sacré, C. 1981 Simulation of two dimensional air flow above complex terrain: roughness and topographical effects. In *Proc. Colloquium on Designing with the Wind.* Centre Sci. Tech. du Batiment, Nantes.

Scorer, R. S.* The use of satellite observations in the study of air flow affected by obstacles.

Scorer, R. S. 1972 *Clouds of the World.* Davis & Charles.

Scorer, R. S. 1984 *Cloud Formation Studies by Satellite.* Ellis Horwood.

Sherman, C. A. 1978 A mass consistent model for wind fields over complex terrain. *J. Appl. Met.* **17**, 312–319.

Simpson, J. E. 1982 Gravity currents in the laboratory, atmosphere, and ocean. *Ann. Rev. Fluid Mech.* **14**, 213.

Simpson, J. E., Mansfield, D. A. & Milford, J. R. 1977 Inland penetration of sea-breeze fronts. *Q. J. R. Met. Soc.* **103**, 47–76.

SIMPSON, J. E. & RIDER, G. C. 1968 Two crossing fronts on radar. *Met. Mag.* **97**, 24–30.

SMEDMAN, A. S.* Some observations of turbulence structure near a wooded coastline.

SMEDMAN, A. S. 1983 Some observations of turbulence structure near a wooded coastline. *Rep.* 68, *Met. Dept Uppsala Univ.*

STEWARTSON, K. & WILLIAMS, P. G. 1969 Self-induced separation. *Proc. R. Soc. Lond.* A **312**, 181–296.

SYKES, R. I. 1978 Stratification effects in boundary layer flow over hills. *Proc. R. Soc. Lond.* A **361**, 225.

TAMPIERI, F.* Two-dimensional stratified fluid flow over valleys.

TAYLOR, P. A., WALMSLEY, J. L. & SALMON, J. R. 1983 A simple model of neutrally stratified boundary-layer flow over real terrain incorporating wavenumber-dependent scaling. *Boundary-Layer Met.* **26**, 169–189.

TOWNSEND, A. A. 1965 The response of a turbulent boundary layer to abrupt changes in surface conditions. *J. Fluid Mech.* **22**, 299–822.

WALMSLEY, J. L., TAYLOR, P. A. & SALMON, J. R.* Some effects of thermal stratification on air flow over three-dimensional hills.

WALMSLEY, J. L., SALMON, J. R. & TAYLOR, P. A. 1982 On the application of a model of boundary-layer flow over low hills to real terrain. *Boundary Layer Met.* **23**, 17–46.

WUNSCH, C. & MINSTER, J.-F. 1982 Methods for box models and ocean circulation tracers – mathematical programming and non-linear inverse theory. *J. Geophys. Res.* **87**, 5647–5662.