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# Air flow and turbulence over complex terrain: a colloquium and a computational workshop

By J. C. R. HUNT[1], F. TAMPIERI[2], W. S. WENG[3] AND D. J. CARRUTHERS[3]

[1] Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Silver Street, Cambridge CB3 9EW, UK

[2] Institute FISBAT - CNR, Bologna, Italy,

[3] Cambridge Environmental Research Consultants Ltd, 3D King's Parade, Cambridge CB2 1SJ, UK

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The third Euromech Colloquium on this topic was held at FISBAT in Bologna in August 1990, in succession to those in 1979 at Munich (No. 113) and 1983 at Delphi (No. 173). About 30 participants came from 10 countries. At the Colloquium it became clear that there have been some significant developments since 1983 in theoretical analysis, computational modelling and field experiments, with new kinds of measurement. As well as papers on improvements in the quantification and understanding of the main, well-known features of these flows, there were also papers on phenomena that had not previously been studied; for example new computations of flows over undulating surfaces driven by buoyancy forces, caused by heating the surface, showed that secondary flows are produced with vorticity parallel to the undulations, while wind tunnel experiments on flows perpendicular to the crests showed secondary flow with vorticity perpendicular to the crests, and with a scale consistent with Craik's (1982) theory which predicted these novel kinds of Langmuir cells. The magnitude of the net drag force on undulating surfaces in neutrally stratified turbulent flows now appears to be moderately well established by different methods, including computations, laboratory experiments, and theoretical analyses. These have clarified the relative magnitudes of a number of contributing mechanisms. The role of Coriolis accelerations ($f$) in atmospheric flow over simple terrain features (lengthscale $L$, height $H$) on the mesoscale (order 30 km upwards) is now better understood. For stratified air flow impinging onto hills rising from a flat plain the Rossby radius ($l_R = HN/f$) is the relevant lengthscale (where $N$ is the buoyancy frequency), but in neutral or convective conditions, such as those which occur when southerly winds are channelled down the Rhine valley, the turning of the wind on a scale of the terrain less than the Rossby radius can also be significantly influenced by Coriolis accelerations.

The recent field measurements by Doppler-sodar (which are installed in several French power stations) produce useful data for comparing with computational models; they also emphasize the need to solve the theoretical question of how best to combine model calculations and measurements within the flow field that exceed the number required to specify the flow in the model. Models of the mean flow and the turbulence have improved to the extent that they can be used in other scientific and practical problems, such as being incorporated into models of dispersion of pollutants, or in models of microphysics and chemical processes in polluted clouds over hills.

† European Research Community On Flow Turbulence And Combustion.

Following the Colloquium an ERCOFTAC† Workshop was held in which the computer codes of such models were presented and compared in detail. It was decided that it is necessary to have a systematic intercomparison of such codes, and also detailed comparisons with the extensive sets of data now available from recent field and laboratory experiments.

The wide range of scales that occur in these complex atmospheric flows ($10^{-2}$ m to $10^5$ m) all have to be considered and calculated in detail, because simple assumptions about the flow (such as that the mean velocity has a logarithmic profile up to a significant height above the surface) are erroneous. Computational models were described that range in complexity from those based on analytical solutions (at low computational cost) to those based on solving discretized equations with large variations in grid sizes to accommodate the range of scales. Novel interactive software was used that enables graphs from different models to be requested and then rapidly displayed simultaneously on a screen for comparisons to be made. This software opens out significant new possibilities for scientific meetings and workshops involving computational fluid dynamics.

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## 1. Introduction

The study of air flow over hills and other changes in the Earth's surface, such as roughness or temperature, is not only of great practical importance but is also an excellent way to explore fundamental aspects of turbulent shear flows and the effects of buoyancy forces. These flows can be considered as perturbations to turbulent boundary layers and to the layers of stratified air within and above the boundary layer. They lead to many different fluid dynamic phenomena but to some extent each aspect of the flow can be analysed and understood separately because each occurs on distinctly different lengthscales (for example ranging from $10^{-2}$ m to $10^5$ m for a hill of scale $10^3$ m in a stratified atmosphere). The geophysical and practical importance of these flows is that they strongly affect many atmospheric processes ranging from the smallest to largest scales. For example there are large positive and negative changes in wind speed, surface shear stress, and fluxes of heat, water vapour and pollutants even over hills of low slope; also hills and mountains can change the direction and pattern of air flow over distances much larger than the lengthscales of the hills themselves.

Many practical environmental problems depend on the local wind, such as those concerning the safety of structures, extraction of wind energy, impact of pollutants, wind damage on agriculture and forestry, and the movement of sand and dust. Thus the manner in which wind changes locally over topography has to be understood and predicted. This has been the main emphasis of much recent research on the topic and previous Euromech Colloquia held in 1979 and 1983 (Hunt, Lalas & Asimakopoulos 1984). However, the spatial averages of these local changes, e.g. the average drag or heat and water vapour fluxes (Taylor, Sykes & Mason 1989), are more important for considering the effect of orography on the weather and climate over distances up to global scale. Despite the fact that these average effects are not well understood, they have had to be estimated for use in computational models.

Research in this subject has developed steadily over the past 10 years (as shown in recent reviews by Blumen 1990; Finnigan 1988) and was the reason for holding this Euromech meeting. Papers on fundamental and practical problems, and also on the local and average effects of terrain on atmospheric flows were included. Research on these flows has been changing with the use of large, fast computers, in part because this enables more complex aspects to be studied, such as the details of time-dependent turbulent flows over non-uniform terrain. As this Colloquium shows, these computational studies are leading to some surprising results. At the other extreme, small computers and simplified algorithms provide time-averaged solutions which both enable non-experts to make practical use of recent research, and also allow air flow models to be incorporated economically into models covering a wider range of phenomena such as cloud physics and chemistry, or dispersion of pollutants.

In order to review these computational schemes an ERCOFTAC Workshop was held following the Euromech Colloquium. Some of the results of that Workshop may be of interest to readers of this journal and are described briefly in this paper, primarily in §7.

Field experiments in this subject have been at least as well controlled as laboratory experiments, but with the advantage of the much higher Reynolds number, so that the different dynamical regions of a stratified turbulent boundary layer could be examined (e.g. Zeman & Jensen 1987; Egan 1984). New features of recent field experiments have been their careful design so as to improve the models further and their use of remote sensing and fixed instruments within the region under study. In fact situations may occur (perhaps following an accident or during an intensive campaign of field measurements) when many direct measurements are available, and there is more than enough information to specify the initial and boundary conditions required by the flow models. In some calculations (Kuo *et al.* 1985) the computed solution is 'nudged' (i.e. corrected) in an *ad hoc* way to accord with local measurements. How to improve such *ad hoc* procedures raises interesting theoretical questions. For example, is it necessary to recast the equations in different forms (perhaps variational), or is it possible to use techniques in fluid mechanics that have been developed in other fields, such as control theory?

## 2. Models of flow over hills – smaller scales

Hunt* (Cambridge) opened the meeting with a review of recent developments on airflow over complex terrain, focusing on what determines the lengthscales and magnitudes of the changes to the flow. He first considered three particular ways in which hilly terrain with lengthscale $L$ (10–100 km), wind speed $U$ and Coriolis parameter $f$ can produce mesoscale effects which can also affect climate and weather: (i) when the Rossby number $Ro = U/(fL)$ is small enough, which typically requires $L$ to be the order of 100 km; (ii) in stable flows of buoyancy frequency $N$, individual small-scale features with height $H$ disturb the flow over a long distance $L_u \sim HN/f$ (Merkine 1975; Newley, Pearson & Hunt 1991), the Alps being a good example where the flow below a height $H^*$ ( $\sim H(1-U/(NH))$ is blocked for a long distance upwind (Tampieri & Hunt 1986); (iii) the cumulative effect of many hills or obstacles of scale $L$ distributed over a distance $L_u \gg L$ can produce mesoscale effects, as seen rather clearly over cities, etc. (Oke 1978).

Even for flow over smaller scale terrain there are also large 'inter-scale' effects. If the atmospheric conditions and the hill shape are such that there is a small region where the flow is separated or is close to separation, then any variation in the small-scale surface features that change the surface drag or roughness $z_0$ ( $\sim 10^{-2}$ m) by, say, a factor 10 can lead to the separated flow region being greatly enlarged or, on the other hand, eliminated (Britter, Hunt & Richards 1981). Similar effects can occur

* Denotes the presenter of a paper at the colloquium.

with heating or cooling (Scorer 1955). This has become a significant problem when assessing wind power on hill tops (Apsley q.v.) or when windmills are clustered on hills.

There are special mechanisms controlling the lengthscales in stably stratified flows; an interesting point is that linear theory (e.g. Smith 1980) for flow over hills is not always relevant; for example nonlinear breaking waves can effectively control the vertical scale and thence the Froude number (e.g. Peltier & Clark 1983). In thermally forced flows over hills, lengthscales may depend on the time since the cooling began (e.g. Blumen 1984) as in the case of katabatic winds which spread onto a plain and keep progressing in a front until destroyed by solar heating the next day! The combination of a synoptically forced flow and katabatic wind has been studied for a steady state (e.g. Fitzjarrald 1984) but the unsteady interaction needs more study.

Until recently computational models of flow over terrain which were focused on detailed investigation of particular mechanisms and idealized flows (e.g. lee waves, flow over sinusoidal surfaces) have tended to be modest in computer requirements. But larger computer capacity has been required for models of flow over arbitrary terrain, where arbitrary initial and boundary conditions were specified, and the governing equations are computed in discretized forms. Recently this situation has changed; calculations using substantial computer capacity have been used to investigate particular processes in detail. For example, second-order closure models of turbulence with seven partial differential equations have been used to show where, over hills, the different processes of turbulence are significant (e.g. Zeman & Jensen, 1987; Hunt, Newley & Weng 1990), and large-eddy simulations have been used to model buoyancy effects (Krettenauer & Schumann q.v.; Schumann 1990). On the other hand, methods suitable for limited computer capacity have been developed to calculate quite complex flows under general conditions, using the results of recent research. For example, linearized models of flow over undulating terrain, using Fourier analysis, are being applied to flow over arbitrary terrain of low slope (Taylor (*a*) q.v.; Walmsley, Taylor & Keith 1986) and for several kinds of stratified flow, provided $F = U/NH > 1$ (Carruthers q.v.). In the case of strong stratification where $F \ll 1$, the flow is approximately horizontal and is approximately modelled by inviscid two-dimensional flow in horizontal planes around the hills. Drazin's (1961) solution has been generalized to flow round hills with arbitrary closed contours using complex variable methods, for which new results and laboratory experiments by P. Geiger and J. C. R. Hunt (unpublished) were presented; the US Environmental Protection Agency has developed a code for arbitrarily shaped hills (Perry & Finkelstein 1990) by approximating each closed contour by ellipses. In the summit layer (see Snyder *et al.* 1985; Smolarkiewicz & Rotunno 1990) other approximations are made. Because these latter models do not require judgement about discretization and boundary conditions, they can be used without much knowledge of fluid mechanics. And because they can be used on small computers they are being applied to many kinds of scientific and practical problems whose solutions depend in part on information about the airflow, such as dispersion of pollution, transport of sand (Weng *et al.* 1990), wind energy, wind damage over forests, cloud physics (Dore *et al.* q.v.).

Recent research indicates that the variation of the turbulence structure over hills also has a general form which can be modelled at a computational level not much more complex than that used for the mean flow. Near the surface the variance of all three components of the turbulence increases and decreases approximately with the local shear stress. Well above the local-equilibrium region the eddy scales are large enough that the anisotropic distortion occurs on a timescale less than the eddy timescale (which can be expressed in analytical form using rapid distortion theory). Between these regions, at the top of the inner layer, all the turbulence processes are active, but it is found that the turbulence variance generally changes monotonically between the two limits described above. Therefore in this limited region approximate formulae can be constructed by interpolation (Carruthers & Hunt 1990). By studying spectra, Mason & King (1985) have shown that the velocity of the largest scale eddies varies over the hill approximately like the mean flow, i.e. for these scales blocking effects dominate the distortion effect (Hunt 1973, p. 674).

For both neutral and stratified flows the outstanding problem is to understand and model the location and nature of separated flows. However, certain general features are beginning to emerge; for example in turbulent flows, separated flow tends to be located over the region where the linearized calculation of perturbation pressure shows it to be positive (Tampieri 1987; Neish & Smith 1991).

An alternative and widely used approach for modelling the flow field in complex terrain is to construct from the measured wind data at a number of positions an interpolated wind field that is mass consistent, so that it minimizes an integral over the flow field. Given enough data the method works well, but the form of the minimizing integral is such that with few data points a symmetric potential-like flow over the terrain is predicted (Lewellen, Sykes & Oliver 1982). (Consequently, if only limited wind data are available it is more accurate to solve the primitive equations by assuming the initial profiles of wind and density.) The new question raised was whether, if there are data available within the flow domain, different variational methods might be devised for the inviscid motion corresponding to different types of stratified flows. This approach would certainly yield better results than the present variational methods where the asymmetric flow over hills is not predicted in stratified flows (see also Thukier-Nielson *et al.* 1989). But the best way of combining data and solutions of the primitive equations is still not known. This is a challenging problem both in conceptual and practical terms.

Taylor* & Gong (York, Ontario) presented the results of two numerical models for turbulent flow over two-dimensional sinusoidal hills (height $a$ and wavelength $\lambda$), the main aim of the study being to calculate the drag. In both models the turbulent stresses are approximated by using an eddy viscosity proportional to $k^{\frac{1}{2}} l_m$, where $k$ is the kinetic energy per unit mass and $l_m$ is the 'mixing length'. In both cases $k$ is calculated from an approximate form of the kinetic energy equation (in which the energy dissipation per unit mass $\epsilon$ has to be estimated). In the first, 'one-equation' method (Taylor 1977) $l_m$ is specified as a function of the distance from the ground $Z$ and the depth of the boundary layer $h$, in the form

$$l_m^{-1} = 1/h + 1/(\kappa Z), \qquad (1)$$

where $\kappa$ is von-Kármán's constant.

This value of $l_m$ is also assumed to be equal to the dissipation lengthscale $l_\epsilon$ so that in the kinetic energy equation $\epsilon = k^{\frac{3}{2}}/l_\epsilon$. In the second method ('$k$–$\epsilon$') (Beljaars, Walmsley & Taylor 1987) the lengthscale was calculated from the equation for $\epsilon$ ($l_m = k^{\frac{3}{2}}/\epsilon$), and calculations were performed when the equations are linearized, because linear models can be applied to arbitrary terrain, using Fourier analysis.

The broad trends for drag were in agreement with those of previous analytical (e.g. Sykes 1980), numerical (e.g. Newley 1986; Jacobs 1987), and experimental investigations (e.g. Zilker, Cook & Hanratty 1977), namely that the form drag is proportional $(a/\lambda)^2$ (when $a/\lambda \lesssim 0.03$) and any separated flow is confined to a narrow region, but the drag tends to be proportional to $a/\lambda$ when $a/\lambda \gtrsim 0.1$ and the flow separates. The form drag was related to very small changes in the phase of the surface pressure, which was found to increase as the surface roughness increases (as shown analytically by Tampieri 1987; Hunt, Leibovich & Richards 1988*a*).

Linear and nonlinear models, in which any horizontal diffusion of turbulence energy was neglected agreed well with each other. But including horizontal diffusion, with an isotropic eddy viscosity formulation, led to pressure phase changes and increases in form drag by approximately 60%, even for low slopes. This strong dependence on the parameterization of streamwise normal stresses was a disturbing feature of these models and further investigation is required.

Weng* & Carruthers (Cambridge) presented the results of a numerical model of turbulent airflow over a single hill, also using eddy viscosity for the shear stress, and a 'one equation' model for the kinetic energy $k$, but with different models for $l_m$ and $l_\epsilon$. It had been found in previous studies (e.g. Britter *et al.* 1981) that the formula (1) for $l_m$ does not allow for the significant changes in turbulent lengthscale that occur, even close to a rigid surface, in separating flow or flows with buoyancy forces. An alternative model, called the '*shear blocking* mixing length' (SBML), was proposed to allow separately for the effects of the surface on the normal components (blocking) and for local shear $(\partial u/\partial Z)$, namely

$$l_\epsilon^{-1} = l_m^{-1} = \frac{1}{h} + \frac{A_B}{Z} + \frac{A_S\,\partial u/\partial Z}{\sigma_w}. \tag{2}$$

where the shear and blocking coefficients $A_S$ and $A_B$ are found to be about 1.0 and 0.6. This formulation differs only slightly from previous forms (e.g. Hunt *et al.* 1989), which had been shown to account satisfactorily for shear flow on flat surfaces (including stratified and reversing flows). In this study of flow over hills, it was shown how, although the lengthscale given by (2) only differed from the ordinary lengthscale given by (1) by about 10%, calculations of the mean flows change by a substantially greater factor. Over the hill top (2) leads to a slightly greater velocity perturbation (by about 10%) than the calculation by (1) (and closer to some experiments), but on the lee side the mean flow on hills of slope $\frac{1}{3}$ was found to reverse using (2) whereas calculations using (1) did not reverse. Further downwind the velocity defect (or negative perturbation) is predicted to be 80% greater and a better approximation to the measurements using the model (2) (the $k$–$\epsilon$ model would also be better because this is another, but more complex model where $l_\epsilon$ and $l_m$ are also implicit functions of the mean flow variations). The authors argued that in their method the boundary conditions are explicitly satisfied at the surface and the numerical solutions converged rapidly (without assuming a local logarithmic profile as is assumed in most $k$–$\epsilon$ solutions, e.g. Chauve & Schiestel 1985).

Belcher & Hunt* (Cambridge) presented a theoretical analysis of the pressure-drag forces on a hill with low slope, where the flow upwind is a turbulent stratified boundary layer. The theory extended the analysis of Sykes (1980), Hunt *et al.* (1988*a*) and Hunt, Richards & Brighton (1988*b*), to account for higher-order terms in the expansion parameter $\log^{-1}(l/z_0)$ (Belcher 1991). (Note that in these models the mean flow perturbation is only affected by shear stress in the inner region.) In neutral stratification the drag (to leading order) is caused by the asymmetric pressure perturbation induced by the greater upward displacement of the streamlines on the lee slope, where the 'inner region' of the boundary layer is thickest. (This is a sheltering effect, but without separation; cf. Jeffreys 1925.) Other causes of asymmetric flow, such as the non-equilibrium structure of turbulence (Townsend 1972) near the surface, and the 'rapid' distortion of turbulence above the inner region (Sykes 1980) were shown to be of higher order in $\log^{-1}(l/z_0)$, although, when calculated, were numerically significant at typical values of $l$ and $z_0$.

All these effects are included in second-order closure models of the turbulent stresses (such as Launder, Reece & Rodi 1975), but are not in lower-order closures, such as $k$–$\epsilon$ or mixing length. The analytical results for the drag were found to agree closely with drag calculated by Newley (1986) from the former models. These were about 40% lower than the drag predicted by computational models which used mixing length estimates for Reynolds stress throughout the flow field (e.g. Jacobs 1987). In a stably stratified boundary layer, with a typical buoyancy frequency, $N$, the drag force is modified by three effects. For weak stratification (i.e. $u_*/(NL) \sim 1$, $U(L)/NL \gg 1$) the primary effects on the drag $\hat{D}$, normalized on the mean velocity near the top of the boundary layer, are caused by the change in the mean velocity profile and the reduction in turbulent shear stress (whose combined effect is a reduction in $\hat{D}$). When the stratification is stronger (i.e. $U(L)/NL \lesssim 1$) the buoyancy forces are significant, leading to lee wave behaviour and the well established increase in $\hat{D}$.

## 3. Mesoscale models

Dalu* (Fort Collins, Colorado) presented some analytical solutions to idealized mesoscale problems developed by a joint group from Fort Collins and Rome. He discussed first the non-hydrostatic perturbations induced in an ideal atmosphere by roughness variations of the ground surface, modelled as variations in the momentum stress. A step change of roughness and a patch of roughness (of Gaussian intensity distribution) have been modelled in a steady uniform crosswind. He showed that the perturbations of the near-surface flow cause internal waves that propagate (ranging in frequency from the buoyancy value $N$ to Coriolis value $f$) and thence transfer momentum to the upper atmospheric layers. He observed that the magnitude of the perturbation is related to the depth of the layer near the surface where the Reynolds stresses are acting. These analytical studies are useful for testing and interpreting mesoscale computations.

Dalu*, Baldi, Guerrini & Pielke (Fort Collins, Colorado and Rome) applied a similar mesoscale model (but now with explicit time evolution) to investigate the atmospheric response to surface thermal inhomogeneities. In this second case the atmosphere is taken at rest, and the amplitude and vertical extent of the forced perturbations are a decreasing function of the ratio between a Rossby deformation radius $l_R = hN/f$ (related to the height, $h$, of the convective layer and $N$, the buoyancy frequency above this layer) and the horizontal scale of the inhomogeneity. For the case of a step change of surface heating between two half-planes at constant value, the lateral intensity decreases approximately as $\exp(-x/l_R)$, $x$ being the distance from the line of change. In discussion, reference was made to recent theoretical work and field experiments reported by Fiedler (1987) which had shown how channelling of westerly air flow to the north along the Rhine valley is strongest in convective conditions. This can be explained in terms of the Coriolis effect and the pressure field produced by the crossflow dipping down into the valley. In fact the turning is determined by the product of Rossby number ($U/fL \sim 1$) and the relative depth of the valley ($H$) and the depth of the convective boundary layer ($h$), provided it is capped by a strong elevated inversion (Wippermann 1983).

Canneil* (*a*) (Chatou) introduced the method of nested meteorological models in his survey of the schemes that have been adopted at Electricité de France to analyse, investigate and forecast wind fields and boundary-layer evolution near sites of power stations. He pointed out the advantages of using fine-scale primitive equation models (like the hydrostatic HERMES, with a horizontal space resolution of 10 km, or the non-hydrostatic MERCURE, with horizontal resolution of 1 km), where the initial fields and evolving boundary conditions are determined by larger scale, synoptic models. (Apparently the results are not sensitive to the precise matching between the different models for different scales.) Despite some shortcomings (like the adjustment of the solution at the boundaries to fit the coarser inflow conditions), this modelling technique provides a satisfactory description of the meteorological variables in small regions of complex terrain. Model results were compared with data obtained from Doppler-sodar remote sounding systems (mean and turbulent velocities routinely up to 1000 m and occasionally up to 4000 m), emphasizing the new possibilities in investigating atmospheric motions on meso- and local scales that have arisen from these new techniques. These measurements and the model results showed approximate agreement. Case studies of transport using trajectories computed from the mean wind field plus 'Lagrangian-puff' models for diffusion were also shown, though without any comparison with experiments.

During the ERCOFTAC Workshop, Canneil* (*b*) (Chatou) discussed in depth some relevant differences in the approximations made in the basic equations in the hydrostatic code HERMES code and the non-hydrostatic code MERCURE; the precise formulation of the pressure field in either kind of model has some element of arbitrariness and has to be specified. Unlike other mesoscale models (e.g. Pielke 1984; Beniston q.v.), in this case the shear stresses are modelled using the $k$–$\epsilon$ model (cf. Weng & Carruthers q.v.), in a form suitable for atmospheric flows. (In general heuristic models and parameterizations developed for engineering and laboratory turbulence may have to be adjusted when applied to atmospheric flows.) The non-hydrostatic code was applied to the large-amplitude and breaking internal waves that occurred over a depth of 10 km in the well-documented Boulder storm described and analysed by Klemp & Lilly (1975). This level of turbulence modelling appeared to be satisfactory even for these unsteady stratified flows.

Beniston* (Lausanne) described a coupled model to investigate wind fields and diffusion in Swiss valleys. Starting from a hydrostatic mesoscale meteorological model, similar to that of McNider & Pielke (1981), he showed how an interpolation scheme could produce a wind field on a finer grid in a given limited portion of the domain of the mesoscale model. Typically there were up to $200 \times 480 \times 20$ grid points on a mesh 500 m in the horizontal and 50–250 m in the vertical. The wind field is adjusted in time with the evolving meteorological fields, and computed with enough detail to evaluate unsteady trajectories of particles released from a source in the domain. Stochastic Lagrangian simulations of dispersion are particularly suitable for unsteady flows that are continuously changing. Some satisfactory comparisons were shown between computed concentrations and measured values (by means of a remote sensing technique using a laser beam, 'LIDAR', across a valley), which indicated that this computational model was suitable for these complex flows (Beniston *et al.* 1990). A computer animation showing plume evolution in a Swiss valley demonstrated the usefulness of novel graphics techniques to enable non-experts to appreciate the qualitative features of such large-scale computations, and make environmental decisions. Running this code for 24 hours of real time took 30 minutes on a CRAY-2 (at a rate of 200 mfps). With the next generation of YMP computers this time will be reduced, which will enable other processes to be modelled more accurately, to include, for example, better resolution of inversion layers and a larger number of chemical reactions.

Ratto, Festa, Lalas, Frumento*, Mosiello & Ricci (Genova, Roma and Koropi) presented an improved mass-consistent code, which is based on NOABL (Traci *et al.* 1977). 'Mass-consistent' models produce a wind field, based on measured data that approximately satisfies both the continuity equation and the assumption that a potential flow field can account for the changes in the velocity between the measuring points. With data supplied at only a few points, further assumptions are usually made, e.g. that the vertical wind speed profiles near the surface are consistent with defined values of surface roughness and stability, using the standard Monin–Obukhov similarity relationships (which are only suitable for flat terrain). In the model (AIOLOS) presented, the boundary-layer depth is modelled using a simple equilibrium formula. The input to the model could either be surface measurements, or the distribution of the synoptic winds above the boundary layer. The latter input has been used in observations over the Greek Islands. These simple models may be most appropriate when there is little input data and the terrain is defined over a large grid.

Sedlak* (*a*) (Prague) briefly reviewed the problem of modelling radiation in mesoscale meteorological models. Then he showed measurements of radiative fluxes at several levels in the surface layer, collected during an experiment in the Kazakstan desert. There was an interesting heating at 370 m above the ground. Comparison was made with a simple radiation scheme, showing that the surface radiation balance calculated from the model compared reasonably well with measurements. He commented that in polluted areas the radiation balance is quite different and cannot currently be computed at all accurately in his model. A boundary-layer model by Svoboda was briefly presented by Sedlak* (*b*). This three-dimensional model is based on numerical solution of dynamical equations and uses an eddy viscosity concept, including dependence on the local Richardson flux number and on the local turbulent kinetic energy.

## 4. Studies of flows with strong buoyancy forces

Krettenauer & Schumann* (Oberpfaffenhofen) presented computations of convective air motion over a two-dimensional wavy rigid surface that is heated at a constant rate. There is no imposed mean flow field. The ratio of wavelength ($\lambda$) to height ($H$) of the undulations varies from 1.0–4.0. Two different codes were used. Large-eddy simulation (LES) for effectively infinite Reynolds number (Schumann & Schmidt 1989; Schmidt & Schumann 1989), and direct numerical simulation (DNS) for Reynolds number $Re = 10^2$ (for typical velocity fluctuations) and Rayleigh number $Ra = 70000$. The DNS results extend those from a previous study by Krettenauer & Schumann (1989) to larger domain size. A surface roughness length $z_0$ defines the surface boundary conditions. In the LES model at the surface the temperature fluctuations on the small scales were larger than in the explicitly resolved scales, whereas all scales (over a more limited range) are resolved in the lower Reynolds number DNS computations. Similar forms of velocity and temperature field were found from both methods. The undulation caused a significant mean component in the convective motion, which consisted of rolls with horizontal vorticity, having a mean motion up the slopes of the undulations (driven by the local mean horizontal pressure gradient). In addition there are large-scale unsteady updrafts and downdrafts with a typical horizontal scale of about $3H$. The two effects tended to reinforce each other for $2 < \lambda/H < 4$, with particularly strong resonance predicted by the LES when $\lambda H \approx 4$. Despite this sensitivity of the mean flow to the form of surface undulations, the intensity and the distribution of the fluctuations of velocity and temperature were approximately the same as those over a level surface, with the possible exception of a 20% change in the horizonal fluctuations. This independence of turbulence of surface conditions in convective motions (but not stable conditions) has been observed in field experiments (e.g. Kaimal *et al.* 1982).

In the discussion it was pointed out that there may be a contribution to the mean flow by another mechanism that occurs when turbulence without buoyancy forces (and without any imposed mean flow) sets up recirculating mean flows on a lengthscale of the undulations because of the gradients of normal Reynolds stresses over the undulations. (This concept was verified by a laboratory study of mixing box turbulence over a rigid undulating surface by Wong 1985.)

Cavazza*, Carnevale, Orlandi & Purini (Rome) presented a computational study of a particular kind of unsteady flow over mountain ridges that is caused when a pair of *vortex couplets* or 'modons' travel in two neutrally stratified layers of depths $D_1$ and $D_2$ separated by an inversion (or density jump) between the layers. The horizontal scales are large enough that the Coriolis parameter is significant. In the computations the radii of the vortices were about 50 km, and the depth $D_1$ ranged from 2500 to 200 m while $D_2$ was fixed at 2500 m. With no hill in the lower layer, the couplets propagate without change, according to the solutions of Stern (1975). A mountain ridge with height $H \sim 0.08D$, was found to have strong effects on the 'modons' (which might model some kinds of 'high–low' weather system). In some cases the lower-layer 'modon' was destroyed, for example by one vortex becoming fixed over the ridge with the other vortex in the pair being deflected along the ridge. (This observation is quite similar to the behaviour of a vortex pair meeting a single vortex, Kiya, Ohyama & Hunt 1986.) The coupling between the layers was weak in the case where $D_1$ is larger than $D_2$ and strong if $D_1$ and $D_2$ are of the same order.

Métais* (Grenoble) reviewed some recent research on the simulations of scalar quantities in homogeneous isotropic turbulence and then presented some new results on temperature fluctuations when the turbulence is stably stratified. This research is particularly directed at answering the question of whether models for the smaller 'subgrid' scales in LES are also appropriate for stably stratified turbulence. Since mountains often generate local regions where the atmosphere has strong stable stratification, the subject of this paper is quite relevant to understanding and calculating fluctuations of temperature and other scalars in these regions.

Results from three different methods for computing the spectra of scalars in turbulence were compared. Fine details of scalar fields in homogeneous turbulence were studied with a large number of grid points ($128^3$) with two different LES codes; in the first one the simplest assumption was made that the small scales act like a local viscosity on the large scales (following Smagorinsky 1963, cf. Krettenauer & Schumann q.v.), and in the second a more complex model was used to allow, at least statistically, for the fluctuating interactions that can cause the subgrid scales to induce large-scale motion in the resolved scales (see Kraichnan 1966; Chollet & Lesieur 1981). The two computations differed significantly in their predictions not only in the details of the spectra but also in the decay of velocity and temperature fluctuations. Although the approach was primarily developed to model turbulence at high Reynolds number, it can also be used at lower Reynolds numbers, so that it is possible to compare with fully resolved DNS (see also Gerz, Schumann & Elghobashi

1989). A satisfactory comparison was presented at $Re = 52$, with a Prandtl number of 1.

From all these studies it appears that the spectra $E_\theta$ of scalars decrease algebraically with wavenumber (e.g. $E_\theta \propto k^{-n}$) even at the large scales, where the spectra velocities $E(k)$ increase with $k$ (e.g. $E \propto k^4$). This means that, on these scales, although velocity fields are smooth, the scalar fields or their derivatives contain sharp fronts. Also, in contrast to the velocity field, the probability density functions (p.d.f.) for the scalars become more non-Gaussian as the lengthscales of the eddies become larger. These results are consistent with qualitative observations of large local gradients of temperature in the weather, and dye or smoke in flow visualization experiments, but now there is a better quantitative understanding (e.g. Lesieur & Rogallo 1989).

In stably stratified turbulent flow the vertical large-scale eddy motions tend to be strongly suppressed, which means that relatively more of the energy is at the smallest scales. However, using suitably small grid scales, LES can be applied to these flows (e.g. Mason & Derbyshire 1990). Also the stable stratification induces internal waves and oscillations in the variance of fluctuating kinetic and potential energy with time. The main new result given was that, although the p.d.f. of the temperature fluctuations is Gaussian, the p.d.f. of the vertical gradient ($\partial\theta/\partial z$) is significantly non-Gaussian. This may be explained in Lagrangian terms because as fluid elements oscillate over a limited distance about a given equilibrium height they are distorted and flatten out at the top and bottom of their trajectories leading to a local positive value of $\partial\theta/\partial z$, so that $\overline{(\partial\theta/\partial z)^3} > 0$. The paper concluded with an optimistic assessment of how the LES method can now be used to compute the complex shear flows in environmental and engineering problems, a view that is not universally shared by other experts in computational fluid dynamics.

## 5. Experiments on airflow over hills

Briatore* & Alessio (Torino) reviewed current methods for physical modelling of flow over hills and rough surfaces, and emphasized the compromises that have to be made because not all the relevant dimensional scaling requirements can be satisfied. They particularly focused on mesoscale flows (over horizontal scales $L$) when the effects of the Coriolis parameter ($f$) are sufficiently important that in the laboratory the stimulated flows have to be modelled on a rotating turntable with water as the working fluid.

For example even when the wind speed $U_0$ is fast enough that the Rossby number ($U_0/Lf$) is of the order of 10, the unsteady motion and vortex shedding in the wakes of mountains are asymmetric, with the cyclonic vortices being stronger (Alessio, Briatore & Longhetto 1983). To simulate the correct profiles of mean velocity and turbulence, grids and bottom roughness are used for studies of air flow and dispersion around power plants and geothermal sites by Electricité de France at Chatou (where there is a 15 m long rotating channel) and ENEL in Italy. Recently, these techniques have been extended to simulate the growth of the boundary layer and katabatic flows on mountain slopes by stable and unstable stratification (e.g. by heating) of the water in the rotating channels.

Gong & Taylor* (York, Ontario) presented the results of a wind tunnel study that was conducted over an undulating surface of 16 waves in a wind tunnel ($2.44 \times 1.83$ m), primarily with the aim of predicting the form drag. The ratio of wavelength $\lambda$ to roughness length $z_0$ was $1.5 \times 10^4$ and $1.7 \times 10^3$ for the 'smooth' and 'rough' cases respectively, and the ratio of height $a$ to wavelength was 0.2. The flow was approximately periodic by the time it reached the 10th wave, at which point the thickness of the boundary layer was about $\lambda$. Over the smooth surface the flow remained attached, but there was weak local separation on the lee slopes. Note that in a boundary layer that is already turbulent, as the roughness increases there is a decrease in the velocity near the surface and the flow tends to separate *more easily* (Britter *et al.* 1981). This explains why in the second experiment, over waves with a rough surface, the flow separated and the speed up over the crest was lower. In the latter case, it was found (as in other investigations, e.g. Zilker & Hanratty 1979) that the pressure distribution was then not symmetrical over the waves, being approximately constant in the separation bubble.

The 'form' drag (caused by pressure) was calculated for both surfaces, and found to be about 90% of the total drag for the waves with a smooth surface, which was consistent with previous measurements (Taylor *et al.* 1989). Surprisingly, the form drag only contributed 50% of the total over rough surfaces. In this case, although there is a larger region of separated flow, the perturbations of pressure are significantly reduced relative to the smooth case over both crests and troughs. A special feature of this study was the measurement of the three-dimensional distribution of flow over an undulating smooth wall, which showed the existence of mean circulations with vorticity parallel to the mean motion and perpendicular to the crests of the undulation. This effect was not found over a rough surface. Taylor suggested that these vortices were caused by the 'centrifugal' instability of the shear flow near the surface in the troughs (i.e. Görtler vortices).

In the discussion it was suggested that these three-dimensional disturbances were too deep to be caused by the Görtler mechanism (which lies close to the surface), but they were close to the mean circulation over an undulating surface as proposed by Craik (1982) which is caused by a similar mechanism of distortion of the vorticity of the mean flow that drives the Langmuir circulation in water flow below surface waters.

Viegas, Monteiro*, Férreira & Lopes (Coimbra) presented a wind tunnel investigation of flow over idealized terrain features, in order to investigate how topography affects the propagation of forest fires. Different measurements and visualizations were made at high Reynolds number, stressing the variability of the flow patterns with the geometry of the obstacles and the angle of incidence to the wind. Three basic configurations were considered: a pair of two-dimensional hills (with their crests perpendicular to the flow placed at various distances apart), three-dimensional hills with radial symmetry, and a quite novel configuration of two triangular prisms joined at a bevelled edge. They showed how in the third case, at the intersection of the slopes, significant flow acceleration could occur depending on the orientation of the wind, which provides an aerodynamic explanation for the anomalous speed of certain forest fires within canyons (Lopes & Viegas 1990).

Artinano, Cano* & Maqueda (Madrid) described an analysis of observations of about 15000 wind and temperature profiles obtained from a 100 m high meteorological tower located in the northern plateau of Spain. A particular selection of only neutrally stratified cases satisfying four different conditions were considered: (i) adiabatic temperature profile; (ii) logarithmic wind profile; (iii) wind direction at three levels within the same 45° sector; (iv) Monin–Obukhov length greater than 100 m. Remarkably, just 43 of the profiles satisfied all the above conditions! From the analysis performed it was evident that there was a marked dependence of most of the parameters of the profiles on the wind direction, i.e. on the topographic features of the surrounding terrain. Some of the non-standard profiles that did not satisfy the criteria were like the profiles of wall wakes (which arise wherever the flow near the wall locally loses momentum, such as occurs in several different ways in complex terrain). As Mason & King (1985) had also found in mountainous terrain, these authors also found significant low-frequency energy in their spectra.

During the Workshop, Taylor* (*a*) (York, Ontario) reviewed the data available from the international experiment of air flow over the Askervein hill on the Hebrides (height about 126 m and half-length of about 250 m). Previous reviews had been published by Taylor and co-workers (e.g. Mickle *et al.* 1988), and a general review of this and other field experiments was published by Taylor, Mason & Bradley (1987). Further recent analysis of the mean wind profiles ($U$ as a function of $Z$) where the distance $Z$ from the surface extends down to 0.5 m have shown that, although the nature of the surface over the hill is the same (small rocks and low heather) as upwind, the local roughness length $z_0^*$ derived from the intercept of a straight line plot of $U$ against log $Z$ over range of height $Z$ (0.5–10 m) shows that $z_0^*$ is about $\frac{1}{30}$ of its value upwind. This is consistent with the theoretical prediction that when turbulent boundary layers are perturbed the standard logarithmic profile near the surface, with the same value of $z_0$, persists but only over a thin layer very close to the surface (less than a distance of order $(z_0 l)^{\frac{1}{2}}$ according to Hunt *et al.* 1988*a*). This result is an excellent example of the very wide range of lengthscales that occurs in these flow problems and confirms the need for very fine meshes in any computations of these flows. Data on the changes in turbulence structure were also presented (referred to by Hunt q.v.).

Also in the Workshop, Canneil (Chatou) described the forthcoming 1991/1992 international experiment to study in detail stratified flow over the Pyrenees.

## 6. Diffusion and deposition

Anfossi,* Ferrero, Brusasca, Tinarelli, Giostra, Tampieri & Trombetti (Torino, Milano and Bologna) presented a model for dispersion in complex flow using Lagrangian particle simulation (a EUROTRAC project). As reference data, wind tunnel measurements of neutrally stratified turbulent flow and dispersion from point sources over single hills of different slopes by Khurshudyan, Snyder & Nekrasov (1981) were used. It was first necessary to devise an algorithm for simulating skewed velocity distributions that are consistent with the observed first, second and third moments of turbulent fluctuating velocities, with the derivatives of the variances of the horizontal and vertical components and with the cross-correlations of the different components, as required by these Markovian random flight models (Thomson 1986; de Baas, van Dop & Nieuwstadt 1986). The two-dimensional geometry of the obstacle and other symmetry considerations meant that the turbulence was homogeneous in the $y$-direction, a considerable simplification. Within the outlined limitations, the model performed well in simulating dispersion in shear flow over flat terrain; interestingly, it was sensitive to the profile of the cross-correlation term $\langle u'w' \rangle$, which is important for dispersion in the lee of a hill. Simple formulae were assumed to describe the distribution of the Lagrangian timescales for the lateral and vertical components $T_y^{(L)}$ and $T_z^{(L)}$, and were adjusted so that the predictions of the simulations for the mean height of the marked particles and their lateral variance agreed with experimental data, following the scheme suggested by Hunt (1985). Not all the results were satisfactory and the discrepancies could not be explained. But generally the paper confirmed earlier studies (e.g. Maryon, Whitlock & Jenkins 1984) that stochastic Lagrangian simulation is the most accurate method currently available for computing dispersion in complex flows, despite uncertainties in Lagrangian statistics. However, these methods may not yet be suitable for practical calculations (e.g. for environmental decisions), because they require substantial computer time.

Bouzom* (Paris) discussed the features of the MEDIA model of transport and dispersion of pollutants at the French Meteorological Service. This model is essentially a mesoscale model with a grid of 7.5 km, 30 levels and 65 × 65 grid points in the horizontal, which has an interface with the dynamic fields computed from the PERIDOT meso-$\beta$ model (on a 35 km grid), operated by the French Weather Service. The transport and dispersion model is based on the numerical solution of the diffusion equation, with a novel vertical eddy coefficient defined as a function of the stability profile, derived from a formulation of the planetary boundary layer by Louis (1979). On scales smaller than the grid, the plumes are modelled individually using standard Gaussian formulae for dispersion from a point source. There is a sink term in the model to account for dry and wet deposition and for radioactive decay as appropriate.

Dore, Choularton & Carruthers* (Manchester and Cambridge) presented a model for the deposition onto hilly ground of pollutants contained in cloud droplets, a process which occurs when the base of the cloud over the hill is lower than the hill height. The model evaluates the flow field over a hill when the upwind boundary layer is capped by an inversion, and then simulates both the droplet growth within the clouds (which form because of the adiabatic cooling as the air flows over the hill top) and the chemical processes in the droplets. In this situation, two deposition mechanisms are important: cloud droplets scavenging by the falling rain, and turbulent deposition of droplets at the ground (Carruthers & Choularton 1984, 1986). The mean flow and turbulence fields were calculated using the three-dimensional stratified turbulent flow model FLOWSTAR (Carruthers q.v.). Separate contributions to deposition were evaluated over different parts of Great Dun Fell (650 m high and half-length 2000 m) in Cumbria, UK, when the upwind inversion height was 1000 m, and also over the Mull of Kintyre. The liquid water deposition rate varies significantly over hills but reaches its maximum near the summit where the droplets reach their greatest size and then have their greatest deposition velocities, and where turbulence levels are high and streamlines approach the surface. The pattern of deposition of sulphate is similar to the liquid water deposition rate except where the concentration of oxidants is low in the air mass of the approach flow. In this case the greatest deposition rates were found to occur on the lee side since it is only when the cloud droplets have been formed for a long period of time that sulphur dioxide is absorbed by the drops and converted to sulphate. In the discussion it was pointed out that computations along the same lines with similar results have been performed by EDF using the HERMES mesoscale code (Canneil q.v.) which required very large computer facilities. But since such computer power is not generally available, simple and fast flow models requiring limited computer capacity are needed in order that the cloud microphysics and the many chemical processes within clouds can be computed with more limited resources. There is also an advantage in using the simpler flow models, because they enable the different aspects of the flow to be investigated separately, to find out the relative importance of their effects on the cloud processes.

## 7. Software

Three kinds of computer codes of flow over complex terrain were presented at the Colloquium and the Workshop. Those based on interpolation of data (described previously by Hunt q.v. and Ratto *et al.* q.v.), and 'analytic' and 'numerical' methods. 'Analytic' computer codes for air flow over hills evaluate several series of mathematical functions whose sums approximate certain analytical expressions, which are themselves approximate (or asymptotic) solutions to approximate equations governing certain statistics of the velocity field! The errors in these methods are understood and are quantifiable.

In this case the approximate analytical solutions were those for the mean velocity and shear stress derived from momentum equations for turbulent flow over undulating rough terrain, in which the turbulent shear stress was modelled by using the mixing-length hypothesis. These solutions were derived by first linearizing the equations and then obtaining the first two or three terms in asymptotic solutions for the thin inner region (where shear stress affects the perturbations) and the deep inviscid outer regions. To apply this solution to flow over a single smooth hill or over arbitrary terrain the analytical solutions are expressed in Fourier series with an infinite number of terms.

The computer code approximates this solution by taking a finite number of terms ($N_F$) and represents the terrain over a distance $X_t$ within a box with finite size $X_b > X_t$ so that the perturbed solution is effectively assumed to be cyclic with a wavelength of order $X_b$. For an isolated hill of length $L$, $X_b$ must be significantly greater than $L$, but for undulating terrain $X_b$ can be of the same order as $X_t$. The only other input to the model is the undisturbed velocity profile (which is not necessarily the same as the solution at the edge of the domain for these analytical solutions). The mathematical expressions need only be evaluated at the $n_c$ points where the computations are required. This computational approach is quite different to the usual 'numerical codes' (cf. Canneil q.v.; Beniston q.v.) where a finite number ($N_d$) of discrete regions of space (or Fourier components in spectral methods) are first defined, and then used to obtain solutions to the discretized (i.e. approximate) forms of the approximate governing equations. All the points in the domain are required for the solution. In principle, as $N_d \rightarrow \infty$, these methods should give an exact solution to the governing equations, because they avoid the approximations used in the 'analytical' methods, for example by avoiding linearization. But for finite values of $N_d$ these 'numerical' methods require lengthier computations ($\propto N_d^4$) compared to the number for 'analytic' methods ($N_F^2 \times n_c$), and the results depend on how the space and time are discretized (especially near the surface). The errors are in general not quantifiable in advance. For complex terrain these 'numerical' methods also have the disadvantage that they depend sensitively on the input and output boundary conditions over the grid and, consequently, in order to calculate flow over undulating terrain in a region of extent $X_t$ (assuming the flow is not known anywhere on the region), the computational domain $X_c$ must be significantly greater than $X_t$ (by several 'wavelengths' of the terrain) in order that the computed solution should develop into the correct form within the flow domain.

The first 'analytic' code MS-MICRO (a microcomputer version of an earlier code MS3DJH (Walmsley *et al.* 1986)) was presented by P. A. Taylor* (*b*) (York, Ontario) and demonstrated on a microcomputer. The mathematical functions in the code have been heuristically developed to 'blend' the inner and outer region, the 'two-layer' analytical (but unsystematic) solutions of Jackson & Hunt (1975) and Mason &

Sykes (1979). The method has been extended to include an arbitrary distribution of surface roughness, by assuming that this effect can be superposed linearly on the effects of terrain (a concept that has been shown to be generally valid where the flow accelerates, but not where there is any significant deceleration such as occurs on lee slopes (Jenson & Peterson 1978; Britter *et al.* 1981)). This was one of the codes run by Buizza *et al.* (q.v.) and compared with methods based on interpolating data. The code describes satisfactorily the speed up of velocity over the tops of hills, but does not account well for the velocity profile very near the ground. On a microcomputer (IBM PC AT) with a grid of 64 × 64 the time taken to computer the flow at 100 points typically takes 10 minutes.

Carruthers (Cambridge) presented and demonstrated a similar 'analytic' code based on the more recent asymptotic three-layer analysis of linearized turbulent flow over undulating surfaces (reviewed by Carruthers & Hunt 1990) which includes effects of surface roughness changes, and stable stratifications in the approach flow. The three-layer analysis satisfactorily matches the solutions in the different layers and brings out the significant changes in the profiles of mean velocity and shear stress that occur close to the surface (see Taylor q.v. §5). Although the analysis is linear, the code agreed rather well with the measurements, but large decreases of wind speed on lee slopes are underestimated. The general criterion for its application is that the slope is less than $\frac{1}{3}$, but this value depends partly on where the calculations are to be performed. Because the analysis is linearized the condition on stratification is that the Froude number based on the height $F_H = U/NH$ is greater than 1. The code also calculates the changes in the variances and lengthscales of the turbulence components, (see Hunt q.v., Carruthers & Hunt 1990). By computing the mean streamlines (directly from the computed velocity field, and not from the linearized analysis) and the turbulent diffusion of fluid particles relative to these mean streamlines, the mean concentration field downwind of localized sources is computed.

Examples were given of flow over isolated hills within square areas of about 20 × 20 km where the terrain height and roughness length was specified at 64 × 64 arbitrarily ordered convenient points (e.g. on contour lines). Some detailed comparisons were given between the computations and measurements from field and laboratory experiments. The flow was computed using 64 × 64 Fourier components. Typically, the flow in one direction at one level is computed in about 5 minutes on a personal computer using a fast chip (INTEL 80386).

The code is now being extended to overcome some of its current limitations. An evaluation study of the same code was described by Apsley* (Letherhead), though he used a large 'main-frame' computer IBM 4381 in order to apply the model to computations of wind energy available to windmills at different sites in hilly terrain. He began by showing how the size of the domain and the grid $\Delta x$ affected the results. For a smooth shape of hill of length $L$ he found that for 2% accuracy on a 64 × 64 grid it was necessary that $X_b/L \approx 8$ and $\Delta x/L \sim 1/8$. He applied the model to assess the annual wind statistics for the wind speed at a height of 25 m at a proposed wind farm site of moderate slope above a partially wooded hill in S. Wales. He compared the predictions with measurements and showed how the wind speed differed significantly depending on its direction over the hill. The predictions were satisfactory except when the wind passed over the wooded area of the hill.

Buizza*, Morselli & Brusasca (Milano, Italy) presented ICARO, a novel system of interactive software designed to run different codes for evaluation of the wind field in complex terrain and to compare their results simultaneously on a Tektronix terminal (4208). At present, ICARO can run, for the same topography and the same upwind conditions, two different codes, namely the 'analytic' code (MS3DJH) described by Taylor (q.v.) and a mass-consistent interpolation code (MATHEW: Sherman 1978). The latter code uses data wherever it is available, particularly data within the flow domain. The software can quantitatively compare the computed fields over the entire domain or over areas defined by the user (for instance, cross-sections) using indexes derived from Anthes *et al.* (1989). Instructive comparisons between the two codes were performed using wind tunnel data from the RUSHIL Experiment (Khurshudyan *et al.* 1981). When only the upwind profiles were introduced the former code (which is based on a solution of the dynamical equations) was, not surprisingly, better because the mass-consistent code assumes, incorrectly, that the perturbation is a form of potential flow perturbation. But if data are specified at vertical profiles at about three locations over the hill, the latter interpolation code is better (which shows the limitation of the model used in this 'analytic' code). It was (for the fluid dynamicists present) a unique experience to ask for comparisons of the effects of using different assumptions, and of using different codes and then, within a few minutes, to see the results displayed simultaneously on the same screen.

## 8. Concluding remarks

This Colloquium demonstrated that significant research progress is still being made in the study of atmospheric flows over complex terrain. It is clear that this subject is benefitting from the use of improved computational resources and the research that has gone into large computer codes, and from new techniques and new initiatives in field measurements. But scientific progress is being made and practical problems are being solved by using these tools to improve our conceptual understanding and in the development of simpler models that reflect this understanding.

The ERCOFTAC Workshop showed how these models can now be used quite widely for scientific and practical purposes and also can be discussed in an unusually open way, when they are written as computer codes with flexible and accessible software. The Workshop also showed how extensive collaboration, mutual testing of codes on agreed data bases and with agreed procedures are essential for the further development and acceptance of these methods in other areas of science and in practice.

Discussion at the Colloquium and Workshop, and with other research groups subsequently, showed that there is an interesting and new aspect to computational fluid mechanics that involves finding methods for the optimum use of both the governing equations of fluid flow and data provided in and on the boundaries of flow domains.

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