Cost Action 710
Pre-processing of Meteorological Data for Dispersion Models

Report of Working Group 4

Wind Flow Models over Complex Terrain for Dispersion Calculations

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Executive Summary

Complex terrain exerts a very significant influence on the atmospheric dispersion of pollutants which can rarely be described by simple models. The simplified algorithms which have been implemented into regulatory dispersion models during the last decades have allowed to deal with phenomena like the first impact of a plume on the nearest hill. These models generally retain flow stationarity and horizontal uniformity hypotheses, that are no longer valid when terrain complexity produces mesoscale and local scale circulations. In the presence of complex circulations the ground-level impact of plumes is often determined by non-stationary 3-dimensional (3-D) trajectories and possibly recirculation of pollutants. 3-D wind fields should therefore be computed and used to drive pollutant transport and dispersion calculations. The computation of 3-D meteorological fields is furthermore necessary if chemical reactions of pollutants have to be accounted for, e.g. for summer smog. After 2 decades of intense research activities and fast progress in computer power, sophisticated wind field simulation models are now more widely available, but true harmonization and validation for regulatory purposes are still lacking.

This report first describes the effects of complex terrain on the wind field for horizontal scales in the range from 2 to 200 km. Then these wind characteriscs and their influence on the pollutant dispersion are analysed so as to distinguish conditions where simplified computations can be applied from those where 3-D wind field computations have to be performed. A terrain classification is proposed, where terrain types are defined on the basis of their morphology and of their influence on the wind field. For each class the wind characteristics are delineated according to their influence on air pollutant dispersion.

The different types of wind field models (linearized models, mass-consistent models and primitive equation - hydrostatic and non-hydrostatic - models) available for application are introduced and their main features and application limits are discussed. Particular attention is devoted to the required input data, initial and boundary conditions. Examples of application performed during the last years are mentioned for each class of models, with literature references. Indications are given about model suitability to the defined terrain classes, computer power needed, as well as about problems encountered.

The computational domain size, space and time resolution are briefly discussed for different kinds of applications. The importance of a sound meteorological survey to characterize the dispersion conditions and to check the wind field model results is being stressed. Model evaluation problems and uncertainties are briefly discussed.

Some guidance to model choice and application is offered by overview tables according to the terrain characteristics. For each case the tables indicate the needed meteorological and terrain input data, application range, computer power and level of expertise.

Even if many models are now available, wind field modelling over complex terrain remains a matter for experienced users and cannot be applied on a routine basis.

Some recommendations related to further research as well as to model improvements, developments and validation are presented. A particular plea is made for more general availability of orographic, physiographic and meteorological data on a European scale to make wind field modelling easier.

This report can hopefully be a foundation for the construction of European guidelines for wind field modelling over complex terrain.

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1. Introduction

Within COST 710, working group 4 (WG 4) had to address complex terrain features and have focused on numerical wind field modelling. Other topics related to complex terrain could not be reviewed. Hence, as an example, mixing height over complex terrain has not been really handled by either working group 2 or 4. Working group 4 have also started an "Inquiry for benchmark exercise on meteorological data pre-processing systems and flow models over complex terrain". With this aim, a comprehensive questionnaire have been worked out and sent to more than 200 scientists. Because of the dimensions of the work involved and of capacity and time shortage, this matter has been left out of this report (Szepesi and Fekete, 1996), as well as a first flow climatology at 850 hPa over Europe drafted by WG 4 members.

The wind field controls the mechanisms of pollutant dispersion (mainly transport and dilution). Improvements in dispersion calculations over complex terrain require realistic wind and turbulence fields; improvements are not possible while retaining the wind homogeneity hypothesis which underlines most of the regulatory Gaussian dispersion models. An accurate reconstruction of the three-dimensional wind field is then a fundamental requirement. The topographic perturbations cause large changes in wind speed and direction and in the turbulent fluxes that strongly affect pollutant dispersion. Hanna and Strimaitis (1990) listed some air pollution situations that are believed to lead to increased concentration in complex terrain: plume impingement on high terrain, pooling of pollutants in valleys, drainage towards population centres and persistence due to channelling inside valleys. To the previous conditions should be added those circulations that can give rise to recirculation of pollutants, like sea and mountain breezes, and mountain wakes.

This report is oriented towards numerical wind flow models over complex terrain intended as meteorological drivers for new generation dispersion models, but also considers the needs of Gaussian-type models. It is neither a comprehensive review of the state of science, nor a textbook, a regulatory guideline or a handbook. Due to the complexity of the matter, it has been conceived as a general and short guidance and check list for the non-experts. In this way, it has to be considered as a step on the way to the harmonization of meteorological pre-processors for the new generation dispersion models. It is complementary to the reports of the other working groups of COST 710. It expresses the scientific expertise of its main authors and has been reviewed and extended by the other working group 4 members.

This report addresses regulatory as well as non-regulatory related purposes, including licensing procedures, abatement strategies and emergency response applications. But it does not imply that its content has been amended by specialists of other European programmes or by policy makers.

The circulation phenomena considered cover horizontal scales in the range from 2 to 200 km (usually addressed as meso-γ and meso-β), and time scales from 1/2 hour to 1 day. These scales include air pollution problems ranging from local scale dispersion from point sources to mesoscale dispersion and urban airshed modelling. Microscale dispersion problems, like street canyons circulation and building wake effects, as well as regional to large scale pollution problems, like long-range dispersion from accidental releases and regional photochemical modelling, are not taken into account in this context.

We examine in the next chapter the types of atmospheric circulation that characterize complex terrain and try then within chapter 3 to single out classes of wind field models that can be considered applicable to each flow situation. Computational resources, input data and user expertise needed by different models are underlined. Chapter 4 is devoted to general requirements, such as model resolution and uncertainties and the needed meteorological studies. The next chapter presents an overview of the preceding ones in table form. After a summary and conclusions, some recommendations are introduced in the last chapter. The reader will also find a lot of references allowing him to deepen his knowledge and judgement.

2. Atmospheric flow over complex terrain

As explained by Hunt et al. (1991), the wind field has to be described in detail, because simple assumptions are often erroneous over complex terrain. Simple computational algorithms (like Gaussian or hybrid models for complex terrain) can be successful only in certain idealised terrain conditions and they can only model the first impact of the plume on the nearest hill, as stated by Hanna and Strimaitis (1990).

Until a few years ago the possibility of employing wind field models was confined to research studies due to the large computer resources requested. Nowadays the computational power of the new-generation personal computers and desktop workstations offers the possibility of using mesoscale flow models to drive pollutant dispersion computation for application purposes.

In this chapter a classification of terrain types with respect to their complexity is attempted. The definition of complexity here concerns not only terrain morphology but also its dynamic and thermal effects on the atmospheric flow. It is then our aim to distinguish the different degree of modification imposed on the flow by topography and land-use features that can be useful for identifying conditions where flow modelling is necessary for a correct description of atmospheric dispersion of pollutants. Moreover a terrain classification will help to describe the types of circulation that can be managed by the different atmospheric flow model classes, described in chapter 3. A background reference of terrain classification on the basis of topographic features and roughness length and directed to wind computation is given by Troen and Petersen (1989) in the framework of the European Wind Atlas. Their classes have been adapted to our scope.

For a general overview on the matter of atmospheric flow over complex terrain, we recommend Blumen (1990).

2.1 Homogeneous and flat terrain

The simplest kind of terrain is the one that can be described as flat and nearly homogenous regarding the surface characteristics that influence the boundary layer flow: soil type (e.g.: clay, loam,...), land-use, roughness, albedo, moisture availability (e.g.: Bowen ratio).

In this situation advection can be neglected, and the system can be considered in condition of local equilibrium. The vertical structure of the atmospheric boundary layer (ABL), and therefore the vertical profiles of meteorological variables, are mainly determined by the surface turbulent fluxes of momentum, heat and moisture, as described by the Monin-Obukhov similarity theory (see e.g.: Stull, 1988, Garratt, 1992, Sorbjan, 1989, Kaimal and Finnigan, 1994). The characteristics of the wind flow (wind speed and direction) are then determined by the flow of synoptic (or larger scale) origin, which is dominant outside the ABL, to which are superposed the variations determined by the local surface fluxes.

The atmospheric flow over flat and homogeneous terrain can be described by simple 1-D models and the vertical profiles of wind and temperature can be estimated on the basis of simple parameterizations (see WG 1 - 3 reports). There is usually no need for a general atmospheric flow modelling, at least for the common needs of pollutant dispersion modelling. This flow condition is the only one where the use of traditional Gaussian-type dispersion models can be considered theoretically justified. It has to be noticed that even over flat terrain Gaussian models can be in error, e.g. in convective conditions when the vertical velocity frequency distribution is skewed (these conditions can be described by "hybrid dispersion models"). Modified Gaussian (steady-state or puff) models can sometimes be used over complex terrain together with wind flow models.

To this "ideal case" can be reduced all those real cases where the patchy surface gives rise to limited variation in the intensity of surface fluxes of momentum, heat and humidity.

The real boundary layer flow can fit the described characteristics only if it is considered at the local dispersion scale (1-20 km).

2.2 Non-homogeneous flat terrain

Some important local to mesoscale circulations are observed over flat terrain characterized by important horizontal non-uniformity. Differences in terrain features are reflected into horizontal variations of surface temperature and turbulent fluxes. Moderate non-uniformity can cause the growth of internal boundary layers due to advective effects (e.g. caused by variation of roughness length; see Kaimal and Finnigan, 1994, Stull, 1988), while strong horizontal gradients give rise to 3-D circulations that normally show daily periodicity.

Important examples of circulations generated by non-uniformity of surface fluxes are the land/sea (lake) breezes and urban heat island circulations.

The land/sea breeze is a thermally driven circulation originated by the different thermal properties of land surface and water (Fig. 1). In a near calm, clear atmosphere, solar radiation heats up a land surface more rapidly than a water surface (that shows very little diurnal temperature change), causing the growth of horizontal temperature gradients. The air over land heats and expands more rapidly than over water, causing the development of a pressure system that induces a circulation directed from sea to land near the surface (sea breeze) and from land to sea at the upper levels (return flow). The circulation is closed by upward vertical motion over land and downward motion over water. During night-time the land cools more rapidly than the sea and the horizontal temperature gradient generated causes the development of a land breeze circulation reversed with respect to daily sea breeze. The daytime sea breeze has a greater vertical and horizontal extent, and its wind velocities are higher than the nocturnal land breeze (for a detailed description of land/sea breeze phenomena see e.g. Simpson, 1994 and Atkinson, 1981). These breezes have been observed even in the case of small lakes. The land and sea breeze wind directions are influenced by the Coriolis force that causes a clockwise rotation of the breeze cell so that winds have the tendency to blow nearly parallel to the coastline during their late lifetimes (around sunrise and sunset).

The urban heat island (UHI) is a phenomena caused by the larger warming of the air above the urban area with respect to the countryside. As discussed by Oke (1987) various causes can be considered responsible for the heat island existence, and their relative role depend on the season, the geographic location and the city characteristics. Among others, the increase of surface heat flux caused by the urban surface properties and the anthropogenic heat flux caused by human activities can be cited. In fair and near calm conditions the UHI generates a circulation that is characterized by the rise of warm air above the city and the convergence of surface winds from the countryside to the centre of the UHI. The vertical development of the UHI circulation is conditioned by the atmospheric stability. In non-stagnating weather conditions the UHI and the urban canopy modify the boundary layer characteristics giving rise to the Urban Boundary Layer (Fig. 2) and to a plume that is transported downwind outside of the city.

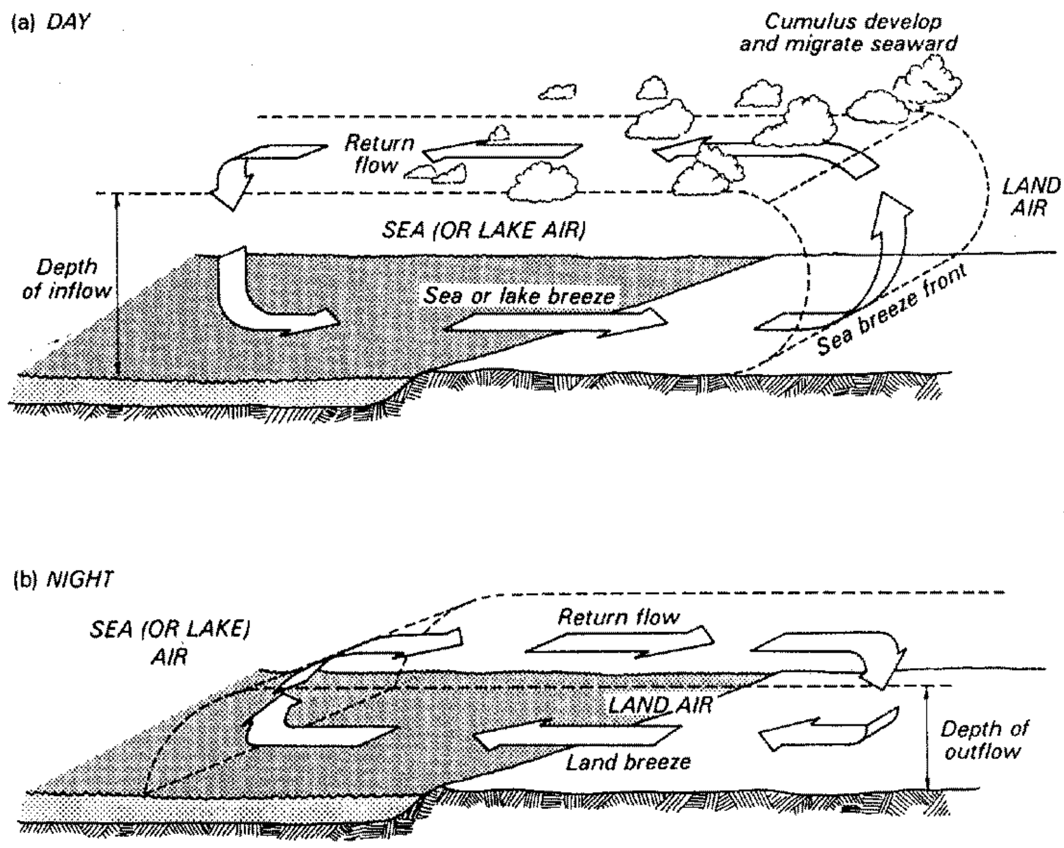

Figure 1: Land and sea breeze circulations across a shoreline by day (a) and at night (b), during anticyclonic weather (from Oke, 1987, p. 168, fig. 5.6). [Reprinted with permission from Methuen & Co. Ltd]

The development of the UHI has been observed even in rather small towns with 10-20 thousand inhabitants. Similar effects can be observed around large industrial complexes characterized by high energy consumption.

These atmospheric circulations can be considered nearly-closed and characterized by periodic reverse of flow direction. Pollutant dispersed in such conditions can be trapped by the flow recirculating inside the area touched by the phenomena. These conditions can be responsible for high concentration episodes. Frequently pollutants emitted near coastal areas are simultaneously subjected to recirculation and to fast chemical reactions. Recirculation of pollutants in land/sea breezes can occur in two ways. Polluted air may follow a recirculatory trajectory by being advected landward in the sea breeze, be lifted by rising air at the sea breeze front and return seaward in the upper return flow. These processes were documented along the East Coast of Spain (Millan et al., 1992) and Vancouver (Steyn et al., 1995). Horizontal recirculation occurs when polluted air is carried landward by sea breeze during daylight hours, and seaward by the land breeze, at night. In both mechanisms, pollutants emitted at ground level can be trapped aloft when the flow at the surface is decoupled from upper winds, creating a reservoir layer of aged polluted air mass, as observed by Millan et al. (1996), and McKendry et al., (1996).The processes of fumigation of aged reservoir layer or effluents emitted above the internal boundary layer were also studied (Portelli, 1982; McRae et al., 1981; Millan, et al., 1984). A pollutant plume released from an elevated source emitting into the stable layer disperses very little as it moves downwind. When it reaches the downwind point where the mixing layer extends upwards to the plume height, the material in the plume mixes rapidly downwards to cause fumigation. This fumigation process can occur also when the polluted air mass aloft is intersected by the growing convective layer (Millan, et al. 1996). To be able to evaluate such dispersion conditions, a correct description (modelling) of the 3-D flow characteristics and its time evolution is of fundamental importance due to the features of non-homogeneity and non-stationarity of the flow.

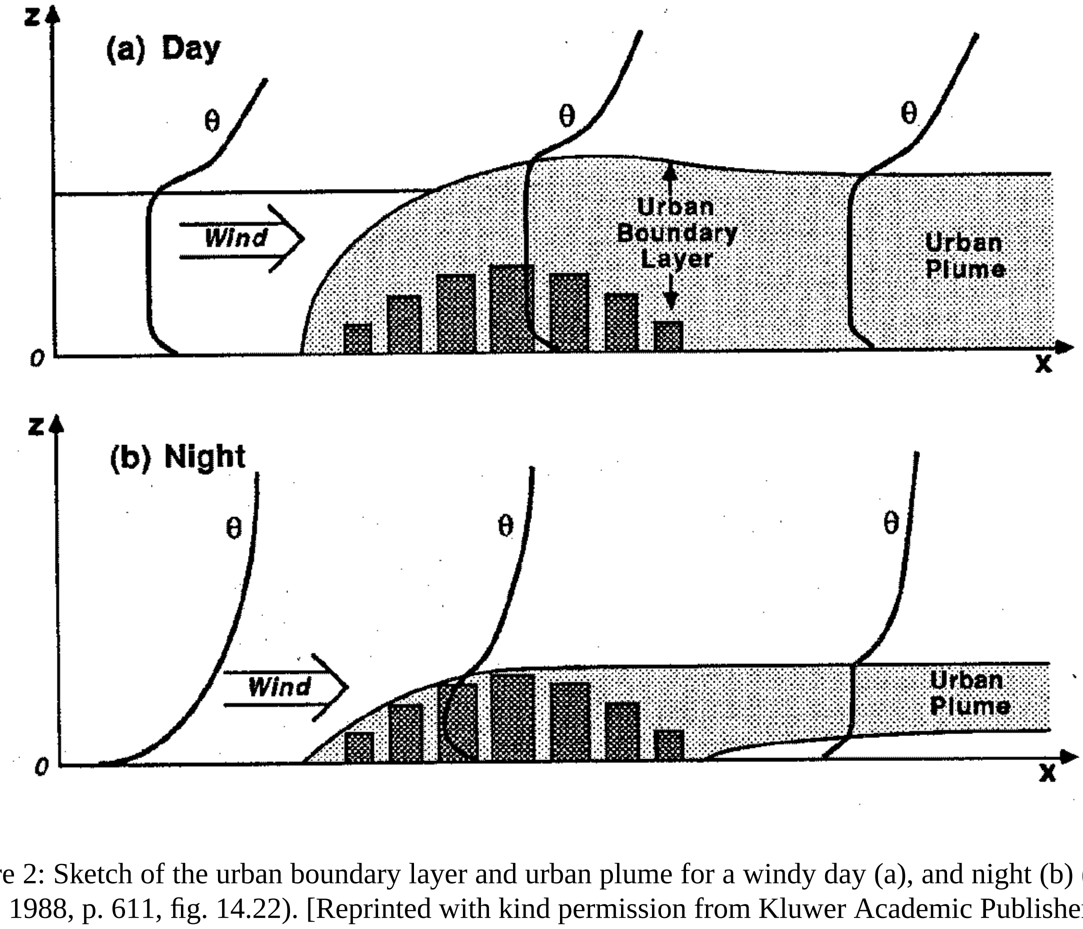

Figure 2: Sketch of the urban boundary layer and urban plume for a windy day (a), and night (b) (from Stull, 1988, p. 611, fig. 14.22). [Reprinted with kind permission from Kluwer Academic Publishers]

The flows described above are classical examples for meso-scale dispersion problems (20-200 km), but are also important at smaller dispersion scale.

2.3 Single hill

The atmospheric flow over a hill of moderate slope is a complex terrain flow case that has been the object of many theoretical and experimental studies during the last 20 years. Experimental studies have been performed both in real atmosphere and laboratories (e.g: Khurshudyan et al., 1981; Finnigan et al., 1990; Baskaran et al., 1987, 1991; Mickle et al., 1988; Frank et al., 1993; Walmsley and Taylor, 1996). Jackson and Hunt (1975) and Hunt et al., (1988a, 1988b) represent the most influential theoretical works relating to flow over low hills, in neutral and stable conditions, where the equations of motion can be linearized. The variations induced on turbulent quantities have been investigated in depth by Zeman and Jensen (1987). These studies allowed a satisfactory knowledge to be reached of the modification induced by a single topographic obstacle, on both mean and turbulent atmospheric variables, in neutral and stable conditions.

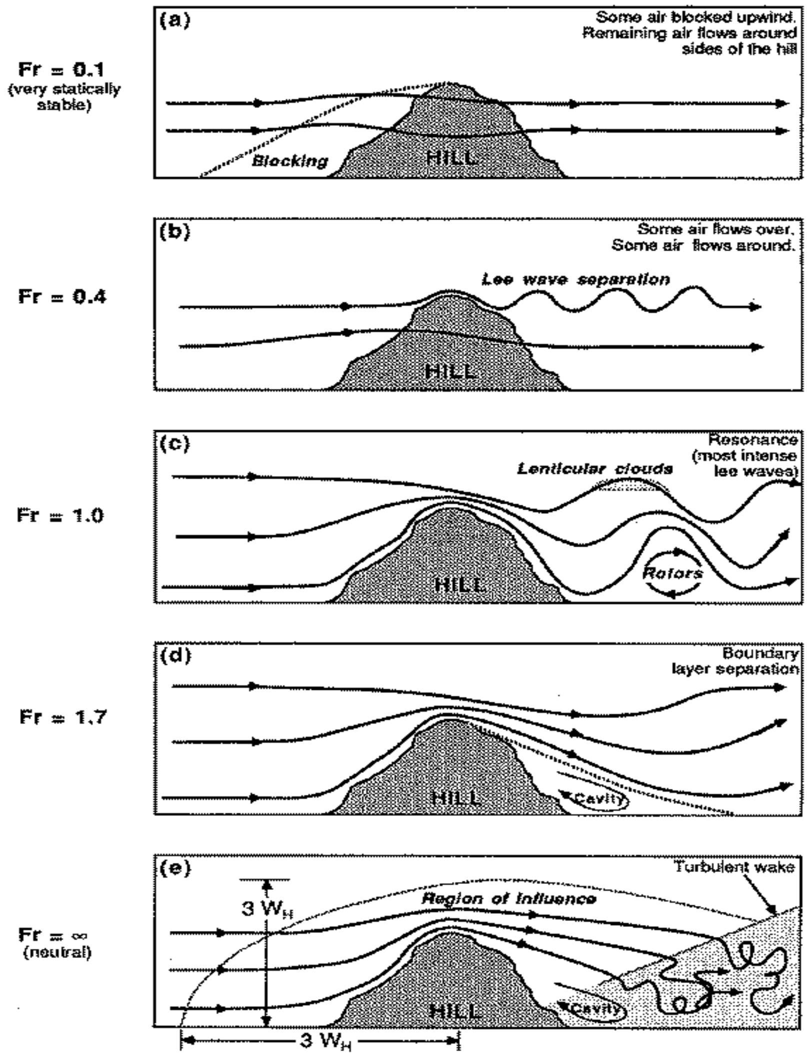

Figure 3: Idealized flow over an isolated hill. Different stability conditions are defined by the values of the Froude number Fr=U/(NL), where U is the wind speed, N the Brunt-Vaisala frequency and L is the length scale of the hill (from Stull, 1988, p. 602, fig. 14.4). [Reprinted with kind permission from Kluwer Academic Publishers]

The major characteristics of the flow over a hill are determined not only by the hill shape but also by its size and by atmospheric stability. In stable conditions the vertical displacement of the air, that takes place when the wind flows over a hill, is opposed by a gravitational restoring force, and the flow is then affected by buoyancy. If the size of the hill is large enough to influence the whole depth of the boundary layer, the buoyancy effects, due to the thermal stratification above the atmospheric boundary layer, can be important also during daytime. In neutral conditions the flow generally shows a deceleration region near the windward foot of the hill and an acceleration on the upwind slope, the maximum speed-up is located near the top of the hill (Fig. 3). A marked flow deceleration is observed on the lee side of the hill, that can cause flow separation and a highly turbulent wake region. The presence of a stable vertical temperature gradient influences both the intensity and the location of maximum topographic perturbations. In stable conditions the kinetic energy of the flow can be insufficient to lift the air over the hill. The wind shows the tendency to flow around rather than to run over a 3-D hill. In such a case the dividing streamline concept can be introduced: the dividing streamline separates vertically the streamlines that pass over the hill from the ones that go around it. The geometrical characteristics of the hill and the steepness of its slopes are directly connected with size and intensity of the wake and with the possible presence of flow separation. The properties of wakes have been reviewed by Taylor (1988).

Even a low hill generates important perturbations on the incoming flow, that can produce relevant effects on the pollutant dispersion. In neutral or weakly-stable conditions the flow over a hill can be described by analytical solutions of Navier-Stokes equations based on linearization techniques as a less expensive alternative to the numerical solution of a complete set of conservation equations. The topographic flow discussed here can generally be considered characteristic of local scale flow.

A single hill can give rise to a thermal circulation system, too. This kind of flow is considered dealing with mountain winds (section 2.6), where its frequency of occurrence is much higher.

2.4 Single valley

We consider here the case of a single valley of moderate depth. The relationship between synoptic scale flows and winds within a valley has been investigated in depth by Whiteman and Doran (1993). They describe four mechanisms explaining winds blowing within a valley: thermal forcing, forced sidewalls channelling, downward momentum transport and pressure driven channelling. The thermal forcing gives rise to the mountain/valley breeze system that is described in section 2.6. The forced channelling produces winds flowing along the valley axis and generates sudden reversal of the wind direction when geostrophic wind moves across a line normal to the valley axis. The downward turbulent transport of horizontal momentum (that occurs over flat terrain too) produces wind directions within the valley that are similar to the geostrophic direction, with a slight turning near ground caused by friction. During pressure driven channelling the winds inside the valley are driven by the component of geostrophic pressure gradient along the valley axis, and wind direction reversal occurs when the geostrophic wind shifts across the valley axis. The relative importance of the different flows depends on the size, depth and width of the valley. The first two mechanisms are more important in narrow and steep-sided valleys, while the last two are more relevant in large scale wide valleys of moderate depth. Therefore there are few situations in which wind speed and direction inside the valley can be predicted from the overlying synoptic wind. Nonetheless for many practical applications the flow inside broad valleys characterized by a flat bottom is locally similar to flow over flat terrain, unless the site of interest is located near a valley side-slope.

The flow over small scale gentle valleys, where downward momentum transport is dominant, can be described by the linear theory. For the analysis of this kind of flow some results obtained for flow over hills can be applied. A specific wind tunnel experiment dealing with flow and dispersion over valleys has been performed by Khurshudyan et al. (1990) and is reported by Snyder et al. (1991).

2.5 Hilly terrain

We can define hilly terrain a topography made by rows of hills and valleys or more generally the superpositioning of single hills. This terrain has constituted a natural extension for the studies cited in the previous sections. Some experimental and theoretical study has been specifically addressed to this kind of orography (Mason and King, 1984; Mason, 1987) It has also been the object of some application of Large Eddy Simulation (Walko et al., 1992; Dornbrack and Shumann, 1992) directed to study the influence of topography and incoming wind intensity on the convective boundary layer development and structure.

Over this kind of terrain, many of the flow characteristics introduced in the previous paragraphs can be retained as still valid, and, if the slope steepness is limited, the linear theory can be considered applicable.

2.6 Complex topography

Complex topography can be briefly defined as the landscape that is normally addressed as mountain. This kind of terrain, made by systems of crests and valleys, that can be characterized by steep slopes, gives rise to thermally induced circulations like mountain-valley breezes, generates mountain waves, and strongly modifies the characteristics of synoptic flow (Atkinson, 1981; Whiteman, 1990; Durran, 1990; Whiteman and Doran, 1993).

The mountain/valley breezes are more easily observed during anticyclonic weather in summer. In such conditions the differential warming of the mountain sides gives rise to horizontal temperature and pressure gradients, that generate winds (Fig. 4, left). The characteristics of the wind systems depend on the geometry and orientation of the valley. The mountain winds can be roughly divided in two classes: slope winds and valley winds. The slope winds are produced by buoyancy forces induced by temperature differences between the air adjacent to the slope and the ambient air at the same height far from the slope (e.g. over the centre of the valley): slope winds blow up-slope during daytime and down-slope during night-time. To maintain continuity a closed circulation develops across the valley, involving air moving downward in the valley centre during the day and upward during the night. The cross valley circulation transports heat across the valley, heating (or cooling) the whole valley atmosphere, and therefore contributes to the development of valley winds. These winds are produced by horizontal pressure gradients that develop as a result of temperature differences between the air in the valley and the air at the same height over the adjacent plain. Valley winds blow parallel to the longitudinal axis of the valley, directed up-valley during daytime and down-valley during night-time. The circulation is closed above the mountain ridges by a return current flowing in the reverse direction. The actual development of thermally driven winds is often complicated by the presence of other wind systems developed on different scales as described by Whiteman and Doran (1993). These thermal winds show important seasonal variation both in frequency and intensity, generally being strongest during summer, while during winter snow covered slopes can generate cold breezes that can last also during the daytime.

The characteristics of mountain/valley breezes can have important effects on the dispersion of pollutants released inside the valleys. Similarly to what has been described for land/sea breezes, the mountain/valley breezes are a nearly-closed circulation where plumes can be trapped and recirculate causing an accumulation of pollutants inside the valley. A flow of thermal or synoptic origin, channelled inside a valley, can transport plumes along the valley towards cities limiting the crosswind dispersion. Smoke stagnation in the bottom of the valleys can be favoured by the temperature inversion that develops inside the valley during the night and is destroyed by the growing convective boundary layer in the morning (Fig. 4, right).

This type of terrain and circulation spans a wide range of scales, from local to sub-synoptic scale. On this kind of topography simple assumptions are no more valid and the flow can be described only by extensive measurements and/or simulations employing models of proved capability.

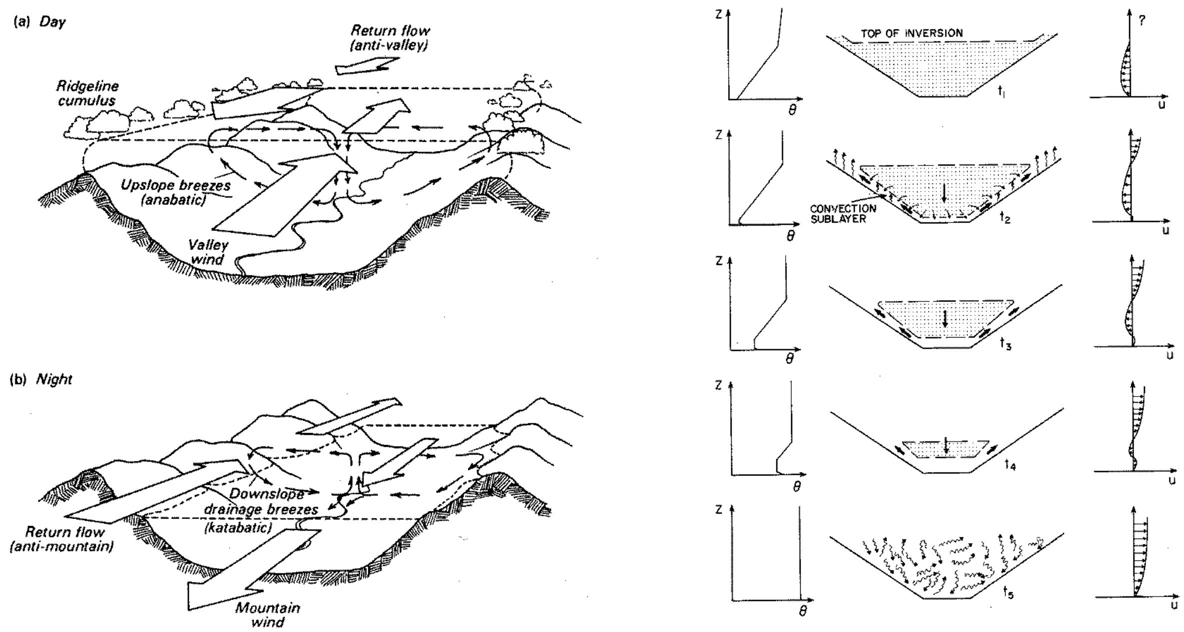

Figure 4: *Left:* Mountain and valley wind system by day (a) and at night (b), viewed with the reader looking up-valley (from Oke, 1987, p. 178, fig. 5.11). [Reprinted with kind permission from Kluwer Academic Publishers]. *Right:* Idealized valley inversion break-up. t1 corresponds to sunset time and t5 to the time when the inversion is broken and a well mixed neutral atmosphere prevails through the valley depth (from Whiteman, 1990, p. 31, fig. 2.27). [Reprinted with permission from the American Meteorological Society]

2.7 Very complex terrain

We would like to distinguish from complex terrain those conditions where the features described in the previous section can be considered extreme, as in regions characterized by the presence of deep and narrow valleys (canyons) surrounded by tall mountains. This kind of landscape is typical of the Alpine region, in Southern Europe. Another example can be given by Mediterranean islands where steep topography adds its effect to coastal flow phenomena, in an area characterized by strong solar radiation. Complex topography can accentuate or counteract the sea breeze depending on the slope orientation. Some studies carried out with numerical models showed that the combined sea breeze and mountain circulations produce a more intense circulation during both day and night than when they act separately (Mahrer and Pielke, 1977). Kurita et al., (1985), Ookouchi et al., (1978), Assai and Mitsumoto, (1978), using numerical models found that mountain ranges contribute to intensified sea breeze by thermal effect but mechanical effect acts in the opposite way. The atmospheric flow can be made even more complex by the influence of non-uniformity of land-use and vegetation cover that sharply varies with altitude. Moreover solar radiation is strongly non-homogeneous due to the effect of terrain slopes and shadow projections. In these situations the flow structure is made extremely complex by the superposing of circulations at many different scales. The local scale flow is often uncoupled from the synoptic flow due to thermal circulation and channelling effects. A complete atmospheric flow modelling over very complex terrain can be still considered a challenge. Very high resolution is needed to resolve horizontal flow complexity and shallow boundary layer like the one that characterizes katabatic flow.

Although generally not critical for environmental studies, topographically induced very strong winds like the foehn have also to be mentioned here.

3. Flow modelling techniques

In the attempt to classify different methods available to face atmospheric flow modelling over complex terrain, a first choice can be to distinguish between diagnostic and prognostic models. We can describe as diagnostic those flow models capable of reconstructing a steady-state wind field starting from a set of initial experimental data. Their equations contain no time dependent terms. Prognostic models are the ones that can describe the time evolution of the meteorological variable fields starting from the initial state and merging the effects of the possible time variation of boundary conditions. They solve full time-dependent equations. It is worthwhile to notice that prognostic models can be applied in a diagnostic way, for example running the model until the simulation reaches stationarity.

Different classes of both diagnostic and prognostic models using different approaches to model atmospheric flow over complex terrain are described in the following. Their theoretical bases are briefly delineated and their input needs are depicted. For each class of models some existing codes are explicitly cited. Of course we do not mean to cite all the existing models but we want to give some examples naming the models that found wider application in the scientific community and that can be considered available for purchase to the users.

The physical simulation with water tank and wind tunnel can offer alternate techniques not treated here.

Table 1 (at the end of 3.2) summarizes the different model types discussed in this chapter.

3.1 Diagnostic Models

Diagnostic models follow two main modelling approaches:

1. simplified steady-state solutions of the Navier-Stokes equations (e.g. linearization techniques);
2. objective analyses of available meteorological data, with some physical constraints (e.g. mass-conservation) imposed.

During recent years diagnostic models have been applied in a few cases to simulate the transport of atmospheric tracers over complex terrain. The mass-consistent model MATHEW (Sherman, 1978) has been applied to simulate nocturnal drainage flow during ASCOT in the Californian Geysers area (Lange, 1984) and Colorado (Lange, 1989), and in Italy during the Lago Brasimone experimental campaign, over the Apennine Mountains (Desiato, 1991). Two-dimensional flow during SIESTA, a campaign carried out over the Swiss plateau, was simulated by LINCOLM, a linearized model (Thykier-Nielsen et al., 1991). LINCOLM and WOCSS (Ludwig et al. 1991) have been applied to drive the dispersion in the hilly coastal terrain at Vandenberg, California (Thykier-Nielsen et al., 1990). The mass-consistent model NUATMOS has been employed to simulate tracer transport of the Cinder Cone Butte experiment (Ross and Fox, 1991). Some studies comparing different models and laboratory and atmospheric data have been performed. Different linearized models (Mason-King Model D, MS-MICRO/2 and BZ-WASP) and a mass-consistent model (NOABL) have been applied over Blashaval Hill (Walmsley et al., 1982, 1990). Two mass-consistent models (COMPLEX and NOABL) have been tested versus long period data in different hilly regions in the UK (Gou and Palutikof, 1990). Mass-consistent (MATHEW and MINERVE) and linearized (MS3DJH/3R and FLOWSTAR) models' performances versus wind tunnel data from the EPA-RUSHIL experiment have been systematically analysed (Finardi et al., 1993). Mass-consistent models have been applied to downscale and enhance resolution of wind fields generated by Global Circulation Models, as well as meteorological pre-processing for regional scale dispersion (Ishikawa, 1994; Mathur and Peters, 1990). Diagnostic wind field models are also used for real-time computation inside industrial plant pollution control networks (Brusasca et al., 1996).

3.1.1 Linearized models

Linearized models are based on linearized solutions of the dynamic equations for boundary-layer flow perturbed by terrain. The linearized theory has been originally developed considering the problem of stationary turbulent flow over a low hill of gentle slope. The atmospheric stability is considered to be nearly neutral and the oncoming vertical profile of wind speed is therefore supposed logarithmic. The flow is broadly divided into an inner layer, where turbulence is important, and an outer layer, where the flow can be considered inviscid (Fig. 5). The terrain shape is analysed in terms of Fourier components; the equations are thus solved in Fourier space; the Fourier transform is numerically inverted to give the solution in real space. Simple closure assumptions are normally used to model the Reynolds stresses. Moreover the linearized theory can be extended in order to model the effect on the wind field of roughness length variations. Linearized models refer to the original work by Jackson and Hunt (1975) (hereinafter JH). The original solution from JH does not provide an exact matching between the inner viscous region and the outer inviscid layer. More recently, Hunt et al. (1988a,b) derived a formally exact linearized solution with proper matching at all heights. To obtain this, the inner layer is split into two regions and the intermediate inviscid layer, where the shear of the oncoming profile is large, is also explicitly described (whereas it was neglected in the original JH solution). This newer linearized solution is not strictly limited to neutral conditions but can be extended to stable stratification. A different approach mixing spectral and finite difference methods to solve equation of motion is proposed by Beljaars et al., (1987). For a detailed description of theoretical development and extensive references we recommend Kaimal and Finnigan (1994).

Linearized models were utilized to drive dispersion models on the local scale and especially to support wind energy turbine siting studies. Their performances have been evaluated versus both laboratory and atmospheric data.

As previously introduced linearized theory has been developed for flow over low hills under the hypothesis of a very gentle slope, such as $H/L \leq 0.05$, where H is the height of the hill, L is its horizontal length scale (Fig. 5), calculated as the half-length at half-height. Further tests and applications proved the linearized theory to give reasonably good results on the upstream side and on the top of hills with $H/L \leq 0.3$-0.4 (Taylor et al., 1987). As expected from their theoretical basis the linearized models are unable to describe flow in the lee region where turbulent wake and separation develop. Another limit to this class of models is the usual hypothesis of a horizontally uniform oncoming wind. In addition, due to the Fourier transform technique applied to solve the differential equations, the topography has to be flat or periodic at boundaries.

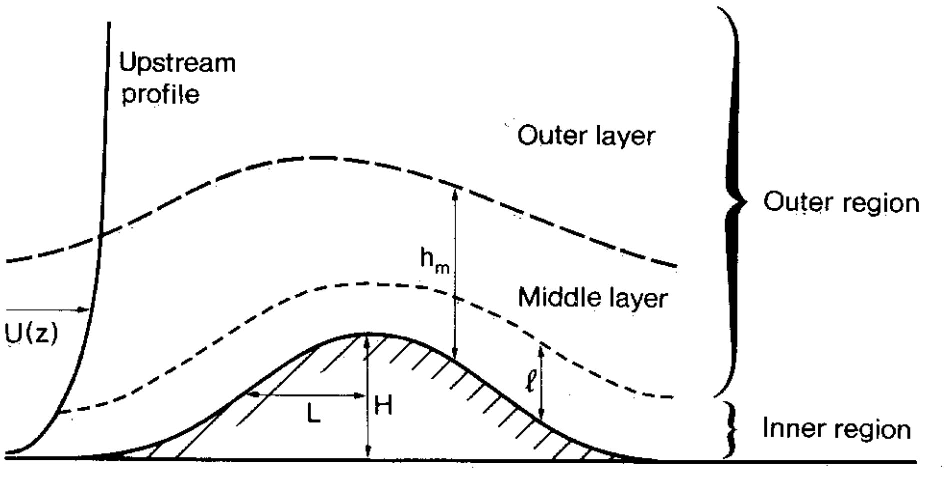

Figure 5: Flow regions for the linear analysis (from Carruthers and Hunt, 1990, p. 86, fig. 5.3). [Reprinted with permission from the American Meteorological Society]

Linearized models need a very small amount of input data:

1. topography and roughness length description in raster format (bi-dimensional arrays of data) or vectorial format (isopleths), depending on different implementations;
2. wind speed and direction at a given height (in case of models limited to neutral flow) or wind and temperature vertical profiles.

Linearized models can be successfully used to reconstruct wind field over isolated hills of moderate slope or hilly terrain. They cannot be applied over mountains where slopes are too steep and the topography too complex. This kind of model finds frequent application in central to northern European countries where a large fraction of the territory is characterized by limited terrain complexity and strong winds.

Linearized models require very limited computer power, they are fast and easy to use and they can normally run on Personal Computers.

Starting from the above theory, different models have been developed during the last fifteen years. Among others the following can be cited:

- FLOWSTAR (Carruthers et al., 1988);
- LINCOLM (Troen and de Bass, 1986);
- MS3DJH/3R or MS-MICRO (Walmsley et al., 1986);
- MSFD (Beljaars et al., 1987);
- NLMSFD (Xu and Taylor, 1992);
- WASP (Mortensen et al, 1993).

3.1.2 Mass consistent models

Mass-consistent models reconstruct 3-D wind fields starting from vertical profiles and near-ground wind measurements, through a two-step procedure. Firstly, wind observations are interpolated to the computational mesh. Then, the interpolated field is adjusted to satisfy mass conservation by minimum possible modification. Such models can describe circulation phenomena implicitly resolved by input wind data, or forced by topography through mass conservation.

The wind data interpolation method plays a crucial role in determining the final wind field features. Different wind fields can be generated starting from the same data and changing only the interpolation method.

The adjustment procedure is generally obtained employing the variational analysis technique. For local scale applications the incompressible form of continuity equation is normally used. When the computational domain extends vertically to the whole troposphere, as needed by long-range pollutant transport studies, the compressible continuity equation (anelastic form) can be necessary (Ishikawa, 1994).

The relative amount of adjustment of the vertical and horizontal wind components in the solution of the continuity equation is usually controlled through the use of a weight parameter called α. Usually α=1 treats horizontal and vertical adjustment equally, whereas larger (smaller) values of α cause adjustment to be effective mainly on the vertical (horizontal) wind component. Thus, the value of α determines the magnitude of vertical velocities, that can favour the movement of the air around or above the obstacles. Generally α is parameterized as a function of the atmospheric stability (unstable: $\alpha>1$; neutral: $\alpha=1$; stable: $\alpha<1$, Sherman, 1978) and, in some models, of topographic features through parameters like the Froude number (Ross et al., 1988; Ross and Fox, 1991) and the Strouhal number (Moussiopoulos et al., 1988). An alternative approach is proposed by Ludwig et al. (1991) who model the stability effect limiting the vertical displacement of the air by forcing the wind to flow over surfaces defined on the basis of the critical streamline concept.

The mass consistent models are widely used in such applied problems like air pollution and wind energy. They can also be used to properly initialize more complex circulation models. Different choices in parameterizations and computational methods are reviewed by Ratto et al., (1994).

The input data used by mass consistent models are:

1. topography and roughness length data over the computational domain;
2. wind speed and direction from surface stations, wind vertical profiles and/or upper air data (each model developer normally states the minimum amount of data needed to run the model);
3. surface and upper air temperature data (requested only by those models that perform 3-D temperature interpolation and/or use parameterizations of atmospheric stability effects based on measured vertical temperature gradient).

Whereas for the horizontal grid spacing Cartesian coordinates are utilised, mass-consistent wind field models have been developed using different kinds of vertical coordinates: Cartesian (Fig. 6), terrain following and z_T (or s) coordinates (Fig. 6). Due to their intrinsic simplicity mass-consistent models do not have theoretical application limits and can be in principle applied to any kind of terrain. Nevertheless, if terrain following or z_T coordinates are used by the model, attention must be paid to orographic gradients because of their influence on the computed vertical wind component: a slope of 45° could be a reasonable upper bound for gradients and a smoothing operation could be necessary if the topography is steeper than this value. Also, vertical computational height (top of the 3-D domain) must be at least 2 or 3 times higher than the highest orographic elevation to avoid very strong speed acceleration over the mountain peaks.

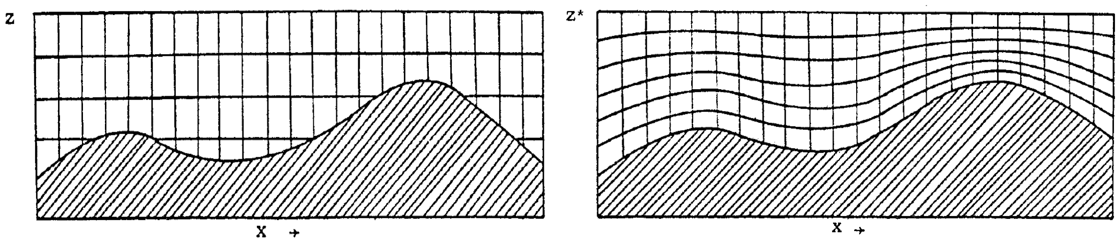

Figure 6: Cartesian (left) and z_T (right) coordinates (From Phillips and Traci, 1978).

The ability of mass-consistent models to effectively describe the main features of a wind field over complex terrain clearly depends on the availability of properly sited input data. To attain a satisfactory description, every main flow feature should be depicted by some input wind profile or, at least, ground-level measurements. A large number of randomly distributed observations would be needed to fully describe the space variability of the wind field over complex terrain, as recently shown by Gross (1996) who compared non-hydrostatic and mass consistent model results. However, with few measurements, the results can be improved optimizing their space location. Therefore, the topographic position of measurements assumes a greater importance in determining the quality of the simulation results, while a limited increase of the number of observations does not necessarily improve the results. In fact, the input data should represent the flow on scales resolvable by the model, while observations are often influenced by local flows related to small topographical features. These data are generally extended spatially in the interpolation phase. Therefore, lacking a better interpolation criterion, a preliminary critical selection of the measurements to be used should be performed in order to avoid odd results. The number of measurements needed to obtain a satisfactory modelling of the main features of the flow is therefore conditioned by terrain and circulation complexity. An example of wind field over complex terrain produced by a mass-consistent model is given in Fig. 7.

Mass consistent models do not need large computer resources. They can normally run on new generation Personal Computers. Workstations' power can be needed for applications dealing with very long time periods and large computational meshes.

Many different models have been developed starting from the late seventies. Some existing codes are reviewed by Zannetti (1990). Among others we quote:

- ATMOS1 (Davis et al., 1984);
- COMPLEX (Endlich et al., 1982);
- CONDOR (Moussiopoulos et al., 1988);
- MASCON (Dickerson, 1978);
- MATHEW (Sherman, 1978; Rodrigues et al., 1982);
- MINERVE (Geai, 1987);
- NOABL (Traci et al., 1977; Phillips, 1979);
- NUATMOS (Ross et al., 1988);
- WINDS (Ratto et al., 1990);
- WOCSS (Ludwig et al., 1991).

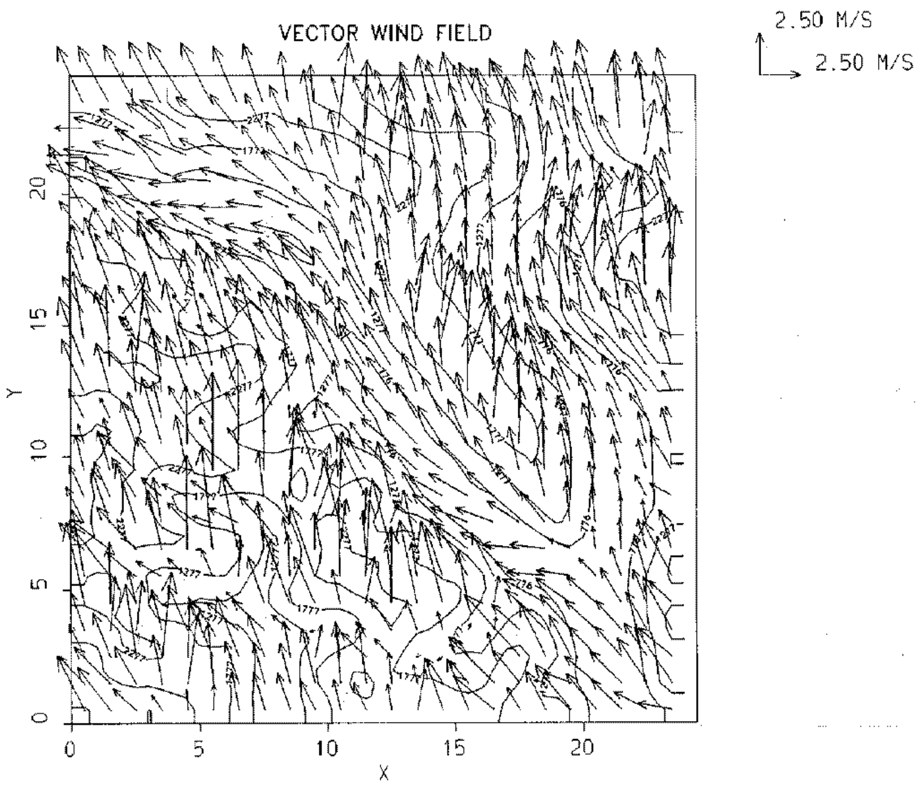

Figure 7: Horizontal cross section of the wind field at the level of 10m above terrain, over the Leventina valley (Southern Switzerland). Computation performed by the mass-consistent model MINERVE (from Ferrero et al., 1995, p. 562, fig. 2). [Reprinted with permission from Plenum Press]

3.2 Prognostic circulation models

Meteorological prognostic models are used to forecast the time evolution of the atmospheric system through the space-time integration of the equation of conservation of mass, momentum, heat, water, and, if necessary, other substances like gases or aerosols.

A main difference among prognostic models is given by the approximations used to implement the conservation equations, e.g.: incompressible, Boussinesq, hydrostatic. Other elements that can distinguish different models are the parameterizations used for the physical phenomena that cannot be modelled explicitly (e.g.: cloud processes, precipitation, turbulence and surface fluxes). The effectiveness and limitation of each approximation or parameterization is strictly tied to the space and time scales to which the model is applied. The different flow assumptions employed in mesoscale meteorological modelling have been recently reviewed by Thunis and Bornstein (1996), who proposed a hierarchy of atmospheric motions and corresponding governing equations to classify models, and explained phenomena that can be simulated by different model classes. For a general introduction to mesoscale modelling we refer to Pielke (1984) and Pielke and Pearce (1994).

Other important model characteristics are connected to the numerical solution of the non-linear partial differential equation system that describes the set of conservation equations. Different grid systems and numerical methods have been used to solve partial differential equations. Various approaches have been chosen to manage initial and boundary conditions. The choice of the coordinates used to describe the computational grid has important consequences, too. Terrain-following, sigma and z* coordinates are normally preferred to the usual Cartesian ones because they allow a better resolution near the ground. Cartesian coordinates description can be useful for flow modelling over very steep topography, where terrain-following coordinates are no more applicable.

Dealing with atmospheric flow modelling mainly to drive pollutant dispersion our main interest is focused on the lower limit of the mesoscale and on the local scale (20-200 km). Inside this range of applications one of the most important assumptions to divide model classes is the hydrostatic approximation. In the following sub-sections some differences between hydrostatic and non-hydrostatic models are explained from the point of view of practical application. The definition of initial and boundary conditions for prognostic models is then discussed.

Prognostic flow models have been applied during recent years to analyse mesoscale circulation and to drive different kinds of atmospheric dispersion models (Eulerian and Lagrangian puff or particle models). A few references to applied studies recently performed are given in the following. Among others reference can be made to the APSIS (Athenian Photochemical Smog Intercomparison of Simulations) study, in the framework of which different models (GRAMM, KAMM, MAR, MEMO, MERCURE, PROMETEO, TVM) have been applied to simulate the atmospheric flow in prevailing land-sea conditions (Kunz and Moussiopoulos, 1995a; Varvayanni et al., 1995; Carissimo et al., 1996). An intercomparison of results obtained by different mesoscale models applied to the APSIS exercise has been presented by Kunz and Moussiopoulos (1995b). The mesoscale model comparison project, named WIND (Wind In Non-uniform Domains), involved the following models: FITNAH, MM4, RAMS and HOTMAC. Project characteristics, model simulations and intercomparison results are described in Pielke and Pearce (1994). A hydrostatic flow model has been applied to drive the

Lagrangian dispersion model LADM for environmental impact assessment of an industrial plant in Australia (Physick et al., 1994). The non-hydrostatic model GRAMM has been applied to estimate the pollutant concentration in the vicinity of an industrial plant located in an Alpine valley (Almbauer et al., 1995). The hydrostatic model PROMETEO has been used to model dispersion over the Barcelona area (Calbò et al., 1995). Summer pollution episodes over the coastal area of Israel have been studied applying the hydrostatic model MM4 (Goldstein et al., 1994). The mesoscale circulation in the Lisbon region has been investigated using the non-hydrostatic model MEMO (Coutinho et al., 1994). The same model has been applied to reconstruct wind flow over Thessaloniki to allow photochemical dispersion modelling (Moussiopoulos et al., 1993). The model RAMS, in its non-hydrostatic mode, has been used to reconstruct atmospheric flow during a tracer experiment in lake breeze conditions (Eastman et al., 1995), to reconstruct the circulation around a volcanic island in southern Italy (Graziani et al., 1996), and to study the dispersion of pollutants emitted by elevated sources near Athens (Kassomenos et al., 1994).

3.2.1 Hydrostatic flow models

The hydrostatic approximations consists in neglecting the vertical acceleration versus the pressure gradient and the gravitational terms. This implies that the vertical scale of motion has to be smaller than the horizontal scale (see Pielke, 1984).

The hydrostatic approximation has been widely used in the past in mesoscale modelling due to the relevant computational advantages. It is not easy to state practical criteria for the limits of applicability of the hydrostatic approximation. From the results of studies performed in the past we can say that hydrostatic models can describe thermal circulations like land/sea breeze as well as stably stratified flow over complex terrain of moderate steepness (anyway the slope angle must be much less than 45˚). Hydrostatic models should not be applied to sites characterized by very complex terrain like the Alpine region or in the local to microscale range (grid size smaller than 1-3 km). But it should be noticed that there are Alpine situations like wide valleys of moderate steepness where hydrostatic models can work rather well. Errors arising from the hydrostatic approximation increase with increasing horizontal wind speed, as well as with decreasing horizontal scale and decreasing vertical thermal stability. According to Bernhardt (1991), the applicability of the hydrostatic approximation depends not only on the geometry of the wind field, but also strongly on the vertical stability, therefore on the time of day and on the season. Based on a scale analysis, Bernhardt (1991) produced a diagram with the hydrostatic and the non-hydrostatic domains for thermally driven slope circulations.

Some mesoscale hydrostatic models in use are:

- CSUMM (Steyn and McKendry, 1988);
- HERMES (Janvier, 1987);
- HOTMAC (Yamada and Bunker, 1989);
- MAR (Gallée and Schayes, 1994);
- MM4 (Anthes et al., 1987);
- PROMETEO (Calbò and Baldasano, 1995);
- URBMET/TVM (Schayes et al., 1995).

It is difficult to quantify mesoscale prognostic models' computer power needs, due to their dependence on the numerical method implemented. Anyway we can say that hydrostatic models can run on workstations, at least if real-time forecast is not needed.

3.2.2 Non-Hydrostatic flow models

Non-hydrostatic models can be considered new generation models in the framework of applied studies (e.g. Schluenzen, 1994). Until recently their huge computer power request confined non-hydrostatic models to the research field. Nowadays the computational power reached by super-computers and the availability of very fast desktop workstations have allowed a much wider development and application of this kind of models that in many fields are going to substitute hydrostatic models.

Non-hydrostatic models have no direct limitations on terrain slopes or scales apart from those due to the particular implementation (e.g. vertical walls can be managed by Cartesian coordinates but not by terrain-following coordinates), even if some limitation on the description of deep flows can be imposed by the form of Boussinesq approximation (Thunis and Bornstein, 1996). These prognostic models are most suitable for describing atmospheric flow over complex terrain, and will probably substitute hydrostatic models for mesoscale applications in the near future. They are often used with nested grids, from coarse to fine resolution, and models' outputs produced on the larger domain are used as boundary conditions on the smaller grid.

Among non-hydrostatic models we refer to:

- ADREA (Bartzis et al., 1991);
- FITNAH (Gross, 1990);
- GESIMA (Eppel et al., 1992);
- GRAMM (Almbauer et al., 1995);
- KAMM (Adrian, 1987);
- MEMO (Moussiopoulos et al., 1993);
- MERCURE (Buty et al., 1988);
- MESOSCOP (Shumann et al., 1987);
- MM5 (Dudhia, 1993);
- RAMS (Pielke et al., 1992);
- TVMnh (Thunis P., 1995).

Non-hydrostatic models require large computer resources. Long-period simulations have to be performed on super-computers like CRAYs, while short-time simulations can be run on workstations.

3.2.3 Initial and boundary conditions

A very important matter related to high-resolution prognostic mesoscale models is the processing needed by meteorological data to define initial and boundary conditions. This kind of model is in fact based on a set of coupled non-linear partial differential equations, whose solution is determined by the initial and boundary values assigned to the meteorological variables. The success of the simulation performed is therefore dependent on correctly specifying the initial state of the atmosphere and its time variation along the lateral boundaries of the model domain. Initial and boundary conditions permit information on the synoptic (or larger) scale flow and its time evolution to be introduced in the simulation.

The input data needed by prognostic models can be identified as:

1. 3-D meteorological fields (at least wind, temperature and humidity) over the whole computational domain to initialize the simulation. 2-D (or 3-D) fields defining boundary conditions on lateral and top limits of the computational domain. The boundary conditions have to be defined for the whole duration of the computation.
2. Topography, soil classification, soil moisture, land-use data and/or vegetation cover, to define the bottom boundary conditions, moreover initial values of ground temperature and humidity can be necessary.

The lower boundary conditions are generally determined dynamically as a function of surface energy balance, that often includes short and longwave radiation transfer. Land-use, soil and vegetation data are used to compute sensible and latent heat fluxes through proper parameterizations, whereas ground fluxes are often modelled. Simulations have demonstrated that initial values of soil moisture are very important in influencing the surface energy budget. In fact, the amount of error in thermal energy storage due to a poor estimate of initial temperature has far less effect on the overlying atmosphere than an error in latent heat energy storage from a poor moisture availability estimate.

For simplified simulations on the local scale, a single vertical profile of wind, temperature and humidity can be used to define horizontally uniform initial fields. For such applications simple choices are also available for the boundary conditions (e.g.: constant values along the inflow boundaries and radiative or zero-gradient conditions on outflow, see Pielke (1984)), where knowledge of the synoptic flow evolution is not required.

A more general and appropriate initialization can be obtained from larger scale model results and/or several observations. The meteorological data distributed by the National Weather Services (NWS) are the basis for such an initialization process. The NWS can distribute gridded meteorological fields from global or regional scale meteorological analysis and model forecast, at fixed horizontal resolution and on standard pressure levels. Observations from WMO synoptic stations and vertical soundings can also be obtained from the NWS. For high-resolution applications the above type of information should be supplemented by local measurements. These data need to be properly interpolated to define the state of the atmosphere at the requested space and time resolution. Often gridded data do not provide sufficient resolution for the initial conditions required by a mesoscale model, and sparse observations are insufficient to define synoptic or regional scale forcing. Therefore some processing is needed to integrate the different meteorological data into 3-D fields required by the mesoscale model. Objective analysis techniques (Daley, 1991) can be applied to define meteorological fields on the nodes of the chosen computational grid, starting from sparse observations and a background field provided by larger-scale analysis. Four-dimensional data assimilation (FDDA) techniques can be implemented to force a prognostic model to follow observations over selected areas of the computational domain, during the whole simulation. This method can be used to create dynamically consistent analysis fields from the mesoscale forecast and asynoptic measured data. The effectiveness of FDDA nudging on the wind and temperature fields generated by a mesoscale model has been recently investigated by Fast (1995). The use of objective analysis and assimilation methods to produce initial and boundary conditions for mesoscale models is reviewed by Sashegyi and Madala (1994).

It needs to be considered that the effect of boundary conditions noticeably influences the model results in the outer part of the computational domain, whose limits have then to be kept far enough from the area where the flow is investigated. The enlargement of the computational domain has the disadvantage of increasing the grid point number and therefore requiring longer computations, unless the space resolution is reduced. A way to manage the problem is the use of grid nesting techniques (as shown e.g. in Fig. 8), where a high resolution grid of limited extension is nested inside one or more lower resolution grids. In this way boundary conditions are moved to the outer and lowest resolution grids. It needs to be stressed that the availability of meteorological data from the NWS is of extreme importance for a correct wind field modelling. Consider that in some European countries access to NWS data is still difficult!

Dispersion calculations for regulatory and non-regulatory purposes often have to compare their results with air quality standards that are formulated on a long-period statistical basis (yearly 98th or 99th percentile, average,...). Due to the huge amount of numerical calculation needed it is not possible to calculate wind fields for time periods as long as all the hours of a year. Therefore some techniques to derive reduced sets of representative meteorological conditions need to be applied. This goal can be achieved by subjective classification of circulations based on meteorological experience and local climatology. Alternatively more objective means of classification can be based directly on data without introducing pre-defined rules. These methods are generally based on cluster analysis of meteorological data, and can be applied to both synoptic and local data. Recently Dittmann et al. (1994) applied cluster analyses to a time series of 850 hPa meteorological analyses to single out 150 weather types to be simulated by a prognostic flow model in the frame of a pollutant dispersion calculation study. Weber and Kaufmann (1995) applied cluster analysis to wind data from a local network of surface measurements including 2 SODAR stations to identify the prevailing kinds of circulations occurring in a region with several valleys (see also Kaufmann and Weber, 1996). Considering a sequence of nearly stationary meteorological conditions the effects of non-stationarity are not taken into account. Therefore conditions like mountain/valley breeze cycles or morning fumigation inside valleys, that can be responsible for important pollution episodes, must be considered separately where relevant.

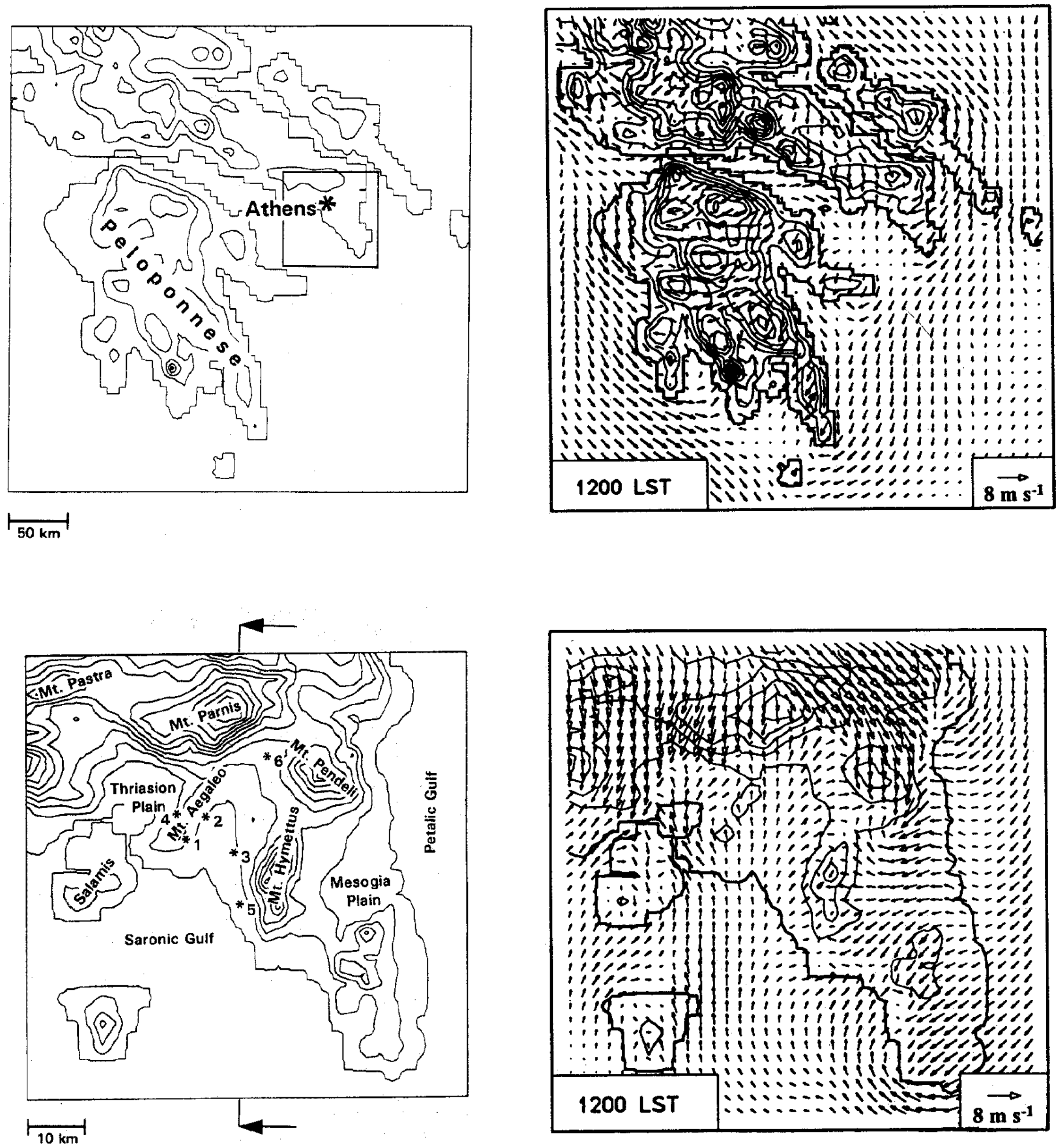

Figure 8: Wind field computations performed by the non-hydrostatic model MEMO over the Athens area. Coarse grid domain (top, left). Fine grid domain (bottom, left). Wind field at approximately 10m above ground level on the coarse grid at 12:00 of 25/5/1990 (top, right). Wind field at approximately 10m above ground level on the fine grid at 12:00 of 25/5/1995 (bottom, right) (from Kunz and Moussiopoulos, 1995, p. 3579-3580, fig. 1 - 3). [Reprinted with kind permission from Elsevier Science Ltd]

Table 1 : Wind flow model types and their main characteristics

Model Types		Main characteristics	Meteorological data required	References	Computer resources	Remarks
Diagnostic Models	Linearized models	Based on linearized solutions of the dynamic equations for boundary layer -logarithmic wind profile	- wind speed and direction at a given height, or - wind and temperature profile	FLOWSTAR (Carruthers et al, 1988) LINCOLM (Troen and de Bass, 1986) MS3DJH/3R (Walmsley et al, 1986) MSFD (Beljaars et al, 1987) NLMSFD (Xu and Taylor, 1992) WASP (Troen et al, 1988)	Very limited computer power (Personal Computers)	They can not be applied over steep slopes and very complex terrain
	Mass consistent models	Interpolated wind fields are adjusted to satisfy mass conservation	- wind speed and direction from ground stations and vertical profiles - in some cases temperature data	ATMOS1 (Davis et al, 1984) COMPLEX (Endlich et al, 1982) CONDOR (Moussiopoulos et al, 1988) MASCON (Dickerson, 1978) MATHEW (Sherman 1978) MINERVE (Geai, 1987) NOABL (Traci et al, 1977) NUATMOS (Ross et al, 1988) WINDS (Ratto et al, 1990) WOCSS (Ludwig et al, 1991)	Limited computer power (new generation personal computers or workstations)	They can be applied to any kind of terrain but attention is required when applied to very steep slopes
Prognostic Models	Hydrostatic models	Simplification of the vertical equation of motion	- vertical profile of wind, temperature and humidity - gridded meteorological fields provided by large scale models	CSUMM (Steyn and McKendry, 1988) HERMES (Janvier, 1987) HOTMAC (Yamada and Bunker, 1989) MAR (Gallee and Schayes, 1994) MM4 (Anthes et al, 1987) PROMETEO (Calbo and Baldasano, 1995) URBMET/TVM (Schayes et al, 1995)	Variable computer requirements (generally workstations).	They can not be applied over very complex terrain and for small grid sizes
	Non-hydrostatic models	Use of full set of equations describing the atmospheric motions	- vertical profile of wind, temperature and humidity - gridded meteorological fields provided by large scale models	ADREA (Bartzis et al, 1991) FITNAH (Gross, 1990) GESIMA (Eppel et al, 1992) GRAMM (Almbauer et al, 1995) KAMM (Adrian, 1987) MEMO (Moussiopoulos et al, 1993) MERCURE (Buty et al, 1988) MESOSCOP (Schumann et al, 1987) MM5 (Dudhia, 1993) RAMS (Pielke et al, 1992) TVMnh (Thunis, 1995)	Considerable computer requirements (new generation work-stations, supercomputers, parallel machines)	No direct limitations due to terrain slopes or scales. They are the more suitable models to describe the atmospheric flow over complex terrain

3.3 Turbulence modelling

Besides the definition of the atmospheric flow, any kind of pollutant dispersion model needs information on atmospheric turbulence. The specific input data needed is different for each class of dispersion model (Gaussian, puff, Eulerian, Lagrangian particle). Dealing with new generation dispersion models we can assume they need information on the second order moments (σ_u, σ_v, σ_w) of the wind components and/or related variables. If these variables are known they can be used directly for model dispersion (e.g. by Lagrangian particle models) or to evaluate different dispersion parameters. Otherwise the vertical profiles of turbulent variables must be estimated on the basis of known parameterizations starting from average variables, atmospheric boundary layer scaling parameters or from other variables like turbulent kinetic energy.

Turbulence modelling should be a topic on its own. In the present section we simply wish to give an idea of the kind of modelling that is made possible by the use of different wind field models. For a general description of turbulence modelling in the atmospheric boundary layer we refer to general textbooks like Sorbjan (1989).

If the meteorological fields are obtained from diagnostic models, no direct evaluation of turbulent variables is normally available. The turbulence has therefore to be evaluated from computed average variables possibly supplemented by information regarding the surface cover characteristics. A first approach is to evaluate dispersion coefficients from the vertical profiles of wind speed and temperature. Often it is preferred to integrate near-ground modelled wind and temperature with surface data (roughness length, albedo, soil moisture) for evaluating Monin-Obukhov similarity scaling parameters (L_*, u_*, w_*, z_i) and finally arrive at parameterizations to evaluate vertical profiles of turbulent quantities.

The use of prognostic wind field models may permit the direct computation of some turbulent variables. The kind of computation performed depends on the closure assumption implemented by the model. Mesoscale meteorological models developed for practical applications usually implement first-order or one-and-a-half order closures. In the first-order closures the eddy viscosity (K_m) is modelled as a function only of average quantities, whereas in one-and-a-half-order closures K_m is a function of turbulent kinetic energy (TKE) and possibly dissipation (ε). The modelled fields of eddy viscosity, turbulent kinetic energy and dissipation can be used to evaluate the needed dispersion parameters. These meteorological models can be directly linked to dispersion models.

It needs to be stressed that the above mentioned turbulence parameterizations and closure assumptions are strictly valid at most in conditions of horizontal homogeneity. The understanding of turbulent phenomena over complex terrain is still severely restricted and is mainly based on experiments and theories dealing with flows perturbed by simple reliefs of limited slope. Model validation has been generally performed only on flat terrain data. The Wangara experiment (Clarke et al., 1971) is surely the most widely used.

Comparisons of model results with experimental data over complex topography are very rare, especially as far as turbulent variables are concerned. Therefore, the effectiveness of the turbulence parameterizations for complex terrain applications is rather uncertain. Very few field studies with extensive turbulence measurements in complex terrain have taken place, among them the Askervein Hill Project (Mickle et al., 1988). More measurements are available from wind tunnel experiments, generally limited to neutral flow over simple topography (Kurshudyan et al., 1981, 1990; Finnigan et al., 1990; Baskaran et al., 1987, 1991).

4. General requirements

This chapter addresses some of the important problems to be handled before starting wind field and dispersion modelling. It concerns activities that can be considered preliminary to any atmospheric pollution study and can influence the choice and the correct application of flow and dispersion models. Caution in the use of such models should be stressed in order to avoid their misuse and fruitless credibility debates (Cirillo et al., 1996). Very complex and sophisticated numerical wind models and their linked dispersion models exhibit strong promising possibilities and they are already in use in many research and application projects. Nevertheless they need a high level of qualification, important personal and computer means and the accuracy of their final results in terms of pollutant concentrations is not proportional to their degree of complexity (Gross, 1991, DWD, 1994, Dittmann, 1994). As stated by Hanna (in Haugen, 1990), “there is a growing recognition of the inherent uncertainty in any kind of atmospheric modelling, due to the effects of stochastic turbulent fluctuations”. Atmospheric circulation model results have therefore to be evaluated by experts.

4.1 Resolution of wind fields

Wind fields usually have to be calculated on a 3-dimensional grid over complex terrain. The requirements on its space and time resolution depend on those of the dispersion calculations. Ideally, calculated concentration fields should have a sufficient space and time resolution so as to allow an adequate evaluation of the detrimental effects of the selected group of sources. According to the definition of the relevant air quality criteria, monthly to yearly averages and/ or frequency distributions of hourly averages for arrays of points closer than 1 km (areas generally smaller than 1 km^2, see VDI, 1992a) are required for local scale studies.

The degree of complexity of the topography has to be considered in the choice of space resolution. It is the primary factor determining the horizontal mesh size. The topographical elements significantly modifying the flow field and the pollution plume(s) within the domain of the dispersion calculation should be duly represented. As a matter of fact, only topographical features with a wavelength larger than at least twice the mesh size can be resolved by a model and the gridded topography should still correctly represent the height, depth and crest lines of the major topographic elements (Lenz, 1996). The minimum resolvable circulation is rather like 3-4 mesh points. As an example, if a slope strongly modifying thermal winds lies between the grid points defined for the wind field calculation, resultant dispersion calculations would not be realistic, even if the latter mesh size is smaller than the former one.

In this context, the slope and orientation of the orographic elements are also important, firstly because of the daily course of the sun, secondly in relation to the choice of the dispersion model (Gaussian-type models only allow for topography gradients lower than 10%). Finally, the spatial and temporal variability of the emissions and the speed of the chemical reactions and other transformations they may undergo can be important. For local road pollution with quasi-ground emissions, this means that the final grid size for the wind field and the dispersion calculations should be of the order of 0.1 km (dispersion domain of the order of 1 to 5 km). The same mesh size is needed for a chimney plume embedded within a complicated valley or subject to slope impingement, but possibly in a wider calculation zone. For analysis of pollution abatement on a regional scale (20 to 200 km), a mesh size of the order of 1 to 5 km should be sufficient unless the topography is very complicated.

Good vertical space resolution is required, especially within the atmospheric boundary layer. The strongest wind variation with height occurs near the ground surface and stack plumes are mainly dispersed at some height above the ground. Accordingly, over complex terrain, it is very important to have enough vertical calculation levels, more closely spaced near the ground than at higher elevation. Normally, the highest level will be well above the highest topography (a practical rule of thumb says that the top of the computational domain should be at least 2 or 3 times the height of the tallest mountain).

For the time resolution, the difference in the needs between level and complex terrain should not be as important as for the space resolution; nevertheless the changes of the differential heating of a mosaic of slopes during the daily course of the sun strongly affect the diurnal cycle of thermal winds. Consequently, the time resolution should allow the reproduction of the main wind patterns during day and night time, with an emphasis on the critical periods (sunrise with wind reversal and fumigation, afternoon convection with anabatic winds, sunset, stable drainage winds). A time dependant wind field, connected to a similar dispersion model, naturally represents an improvement and permits the simulation of episodes with recirculation phenomena.

Not too important for statistical analysis, but of utmost relevance for prognostic predictions in emergency cases over complex terrain, the right “timetable” of the changes in the predicted wind fields should be considered (examples: onset of a valley wind, windturn due to the passage of a front,...). Although the 4 sophisticated models involved in the WIND project were able to reproduce, with good accuracy, the diurnally forced upslope and downslope winds for the first validation experiment, including their times of onset, they seemed unable to adjust sufficiently rapidly to the imposed larger-scale changes (Pielke and Pearce, 1994).

Due to the high number of numerical calculations, it is hardly possible to calculate wind fields and concentrations for all the hours of the year. The conventional statistical distribution of wind directions, speeds and dispersion categories in bins is not any more a practical way. Therefore, techniques to derive sets of representative dispersion situations are necessary, not only taking into account the surface wind but also the wind and temperature stratification. Statistical methods like clustering have been presented in chapter 3.2.3. The technique of reducing the whole year to a set of meteorological situations has already been extensively used for Gaussian dispersion models. It should be based jointly on large scale meteorological situations (weather types) and on local measurements and observations and should lead to a selection of 25 - 100 episodes (Lehmann, 1995). Such a reduction based on a thorough meteorological analysis has the advantage of beginning each impact statement with a screening of the most relevant processes for the particular problem. For the analysis of critical situations, time dependant episodes will often need to be simulated (summer smog, wind reversal,...).

Beside the wind field, when required, the relevant scaling parameters of the boundary layer should be given on the same resolution (L_*, u_*, w_*, mixing height). Over complex terrain, these variables behave differently than over flat terrain and corresponding schemes exist only in rudimentary form.

4.2 Meteorological scoping study

Each wind field and dispersion modelling study over complex terrain should be based on a sound meteorological analysis whose main goals are threefold:

- selection and description of the relevant wind field situations,
- preparation of the needed input data for the models,
- check of the wind field results.

Rather than cover all these topics, we will illustrate them hereafter for the case of the slope and valley/mountain wind regimes and give the scope of the study needed. Let us begin with a general conceptual description (see also chapters 2.4 and 2.6).

These thermally driven quasi-periodic wind systems (day/night) are not restricted to steep slopes or deep Alpine valleys or weak-gradient synoptic conditions, although they are best seen there. The layer of slope winds is, at best, several tens of m thick, with speeds of a couple of m/s. Up- and downvalley winds can comprise the entire valley atmosphere up to crest height, their maximum speeds can attain 5 m/s or slightly more. The slope wind circulations follow sunrise and sunset closely, whereas the thermal circulations in tributary valleys and in the main valley show an increasing time lag, with upvalley winds starting several hours after sunrise. The channelled valley flows act to force plumes repeatedly across the same areas and thereby to increase mean concentrations and local deposition of pollutants. Sunlit slopes will attract plumes. Although wind speeds are generally weak and stable/unstable conditions must be distinguished, the slope layer and the valley bottom must have generally increased turbulence and dispersion. To the extent, however, that the respective circulations have subsiding branches further away from the earth's surface, static stability will be strengthened there and the level of turbulence may be duly suppressed. Additional complications can arise, for example around Alpine or pre-Alpine lakes (Vergeiner and Dreiseitl, 1987).

In such a case, the meteorological study has to analyse the statistically relevant dispersion conditions and search for critical situations as regards the type of pollutant sources concerned. Prior to the wind simulations, an independent local meteorological analysis has to be performed, based on local meteorological measurements and observations as well as on conceptual models found in the meteorological literature (e.g. Stull, 1988). Not only good surface measurements are necessary for diagnostic interpolations, but also profiles which are further strongly recommended for a check of the results of model simulations. Local observations and experiences can be a valuable help (e.g sailors, gliders with daytime and fair-weather bias, of course, smells at night), also if mixed wind systems are apparent with synoptic forcing added to the thermal forcing. Hence, the synoptic flow conditions influencing the different local circulations should be considered to better identify the conditions to be simulated. For prognostic predictions in emergency cases, local/regional measurements are required (see e.g Gassmann et al., 1996) and additional regional wind predictions based on an operational high resolution numerical weather prediction model are highly recommended.

The model input data (initial and boundary conditions) and the model parameterizations have to be properly selected. As an example, if the slope wind circulations prove to be important for the specific problem, the conceptual description given above helps to fix the model resolution that permits simulation of the cases selected. The representativeness of the available meteorological measurements, especially wind, has to be checked, taking into account the mesh size chosen for the simulation. For example, a wind measurement is useless if it is located in a mountain wake or if it is representative of flow at a scale smaller than the model resolution. After completion of the first wind simulations, their results have to be compared with observations and conceptual models. No numerical model should be trusted to give good results without appropriate validation.

It is evident that the level required for the meteorological study increases strongly with terrain complexity.

4.3 Model practice, evaluation and uncertainties

In some countries guidelines have been issued to promote the adoption of best practice in the use of mathematical models of atmospheric dispersion. The British example (Britter et al., 1995) comprises considerations under the following ten headings, which can also apply for wind field modelling: Statement of context and objectives, Justification of choice of modelling procedure, Use of software implementations of modelling procedures, Input data, Presentation of results and conclusions, Explicit quantification, Sensitivity analysis, Uncertainty and variability, Quality assurance of models, Auditability. This document can help to state guiding criteria for choosing an appropriate model. It also gives advice on methodological topics.

Hanna (in Pielke and Pearce, 1994) discusses the evaluation of environmental models, addressing the scientific component (Peer review, Comparison with analytical solutions, Diagnostic evaluation of components, Conservation of mass and energy, Code verity and Visual analysis of maps of wind vectors), the statistical component (statistical tests), as well as the example of mesoscale and regional wind fields. It must be remembered that even over flat homogeneous terrain, mesoscale turbulence fluctuations can cause variability of hourly averaged wind speed of 1 or 2 m/s over distances of a few kilometres (Hanna and Chang, 1992). Quoting Hanna again: “ It appears that the rms errors in near-surface wind field predictions by mesoscale and regional models are characterized by minimum values of about 1 m/s for wind speed and 20 - 40 degrees for wind direction”.

According to Hanna (Hanna, 1994), the inherent difficulties of the two types of wind field models described in chapter 3 (diagnostic and prognostic) for mesoscale applications, are summarized in Table 2. Similar problems can be also encountered with local wind simulations.

Table 2 : Inherent problems with mesoscale wind models (Hanna, 1994)

With diagnostic models	With prognostic models
There are never enough monitors to satisfactorily resolve the flow fields, The observed winds contain errors and may be unrepresentative, The model attempts to force mass continuity in a method highly dependent on the assumed mixing depth and the terrain slope	The gridded wind fields “look” smoother than the observed wind fields (i.e., there is a lack of turbulent energy at scales of one to ten grid distances), The wind fields sometimes miss the strength and timing of fronts, sea breezes, and other phenomena, Flows due to storm complexes are not resolved

It should also be noticed that the nocturnal stable dispersion conditions (SBL) are still not well parameterized. Up to now, most research work has been focused on the convective boundary layer, whereas more frequently the stable boundary layer is the place of critical conditions, even without topography: strong wind shears and inversions, non-stationary and non-local behaviour (topographic and other influences propagate horizontally and vertically through the SBL). As a limiting case, elevated puffs and plumes, decoupled from the surface, must be assumed to be capable of travelling virtually without additional dispersion for several kms after their initial dilution near the source. This is without mentioning very extended concentrated plumes over water. Although different studies and experiments directed to investigate plume impingements on the first hill took place during the recent years (e.g.: EPA CTMD Project, Cinder Cone Butte experiment, RUSHIL and RUSVAL experiments, German Sophiehohe hill experiment), there is a lack of knowledge in the interaction of such concentrated plumes/puffs with irregular hills in weakly shifting wind and concomitant pressure fields.

Therefore, the questions of model validation and of the uncertainties of its results within the modelled area should be addressed appropriately in each dispersion analysis, also in relation to the wind field simulation.

5. Requirements, guidance and check lists

This chapter summarizes the preceding ones, mainly in the form of synthesized tables. We recall that a thorough definition of the requirements of the dispersion calculation is necessary prior to the equivalent definition of the wind field calculations. Evaluations of a yearly average or of 99% - percentile of a pollutant concentration, for an elevated point source, for road traffic or for many different emitters, with or without chemical reactions, on a local or regional scale,... lead to very different requirements on the wind field calculations.

5.1 General overview

The following Table 3 gives an overview on the types of model to be used and on the related next summary tables and scales, for the different classes of terrain from lowest to highest complexity. This table oversimplifies the distinction between the different cases, but it is not easy to find out simple and comprehensive criteria for all modelling purposes.

Table 3 : Overview Table

Type of terrain	Main type of diagnostic wind model	Main type of prognostic wind model	Summary Table	Main scale
Homogeneous and flat terrain	1-D		4	local
Non-homogeneous flat terrain without 3-D circulations	piecewise 1-D, LFM		4 or 6	local
Single low hill with moderate slope	LFM		6	local
Hilly terrain (low hills / moderate slopes)	1-D, LFM		4 or 6	local
Single simple large valley (central core)	1-D, MCM	HM	4 or 5	local
Non-homogeneous flat terrain with 3-D circulations	MCM	HM	5 or 7	local - regional
Complex terrain	MCM	HM, NHM	5 or 7	local - regional
Very complex terrain	(MCM, with caution)	NHM	7	local - regional

The different referenced models are:

- 1-D: 1-Dimensional models (z)
- LFM: linearized flow models (for dynamic flows)
- MCM: mass consistent models
- HM: hydrostatic models
- NHM: non-hydrostatic models

Where no prognostic model is mentioned, it is clear that HM and NHM can be used to describe small-scale flow from synoptic information. Prognostic models (HM, NHM) can also be applied in a diagnostic way.

5.2 Homogeneous and flat terrain

Table 4 summarizes the needs and guidance in case of homogeneous and flat terrain. It is intended here as a reference table with which the other ones are to be compared.

Table 4 : Wind flow models for homogeneous and flat terrain

Requirements on wind flow results	Horizontally homogeneous vertical wind and turbulence profile
Wind flow models	Simple 1-D models (vertical profiles estimated on the basis of parameterizations according to WG 1 to 3)
Needed input meteo data set	From 1 climatological station representative of the studied area or from a regional or global operational weather forecast model (one (interpolated) grid point)
Terrain pre-processor	Evaluation of the homogeneous roughness based on land use
Validity of flow	Local scale (up to 10 - 20 km)
Meteorological study needed	- Basic description of the dispersion climatology, inclusive discussion of representativeness of the surface meteo data for the whole calculation domain (measured vertical profiles represent an improvement) - Search for adverse dispersion conditions and check on their wind simulation
Special problems	Calm wind
Computer and data management requirements	Very small (PC)
Needed level of expertise	Low
Remarks	For reasons of simplicity, regulatory dispersion calculations are mostly performed on such an ideal hypothesis. The same can still be used for screening evaluations in moderately complex cases with an appropriate discussion of the results. If the target area (where relevant concentrations are expected) within the calculation area can be considered as homogeneous enough in its wind field, then dispersion calculations for this ideal case can be used in a detailed impact analysis.
Dispersion models	- It is the only case where traditional Gaussian-type dispersion models are theoretically justified - Preferably new generation dispersion models

5.3 Non-homogeneous flat terrain

A meteorological screening analysis should enable one to decide if significant 3-D circulations appear in the calculation domain, in particular if they are nearly-closed. Diurnal cycles of measured wind speed and direction as well as a basic meteorological expertise are needed. Then, their possible influence on the dispersion calculations (e.g. fumigation with high concentrations) has to be evaluated before deciding to include or neglect them.

Tableau 5 : Wind flow models for non-homogeneous flat terrain with 3-D circulations

Requirements on wind flow results	3-D or 4-D wind and turbulence with enough resolution to resolve the features of the circulations (on the order of 1 km of horizontal resolution)
Wind flow models	a) Mass consistent models (3-D) b) Hydrostatic flow models (3-D or 4-D)
Needed input meteo data set	a) From an array of surface wind stations and of some wind and temperature soundings resolving the features of the 3-D flow b) Single profile, but preferably more detailed initial and boundary conditions
Terrain pre-processor	Land-use data and soil classification
Validity of flow	- Local scale (1-20 km) and regional scale (20 to 200 km)
Meteorological study needed	- 3-D description of the dispersion climatology, including diurnal and seasonal cycles, as well as analysis of representativeness of the different stations - Synoptic flow conditions influencing the different local circulations - Search for adverse dispersion conditions and check on their wind simulation (analogous case studies, conceptual models,...)
Special problems	a) Adequate set of input data b) Initial and boundary conditions a-b) Validation of resultant wind fields (e.g. unrepresentativity, oversmoothing)
Computer and data management requirements	a) small to moderate (PC or workstation) b) moderate (workstation) (in both cases, depending on the number of simulated cases)
Needed level of expertise	A good understanding of boundary layer flows and of computer models
Remarks	The choice of the model has to be duly justified and documented
Dispersion models	- New generation dispersion models (Lagrangian or Eulerian)

5.3.1 Without 3-D circulations

This case can be assimilated to the first case, where regions (patches) with a different roughness for each one are defined within the calculation area. For each region, a specific profile is then derived taking into account internal boundary layers. A new generation dispersion model allowing for such heterogeneity is required. Table 4 needs only the above mentioned modifications.

5.3.2 With 3-D circulations

If significant 3-D circulations occur, then the following Table 5 applies.

Table 6 : Wind flow models for single low hill of moderate slope

Requirements on wind flow results	3-D wind and turbulence with enough resolution to resolve the features of the flow (on the order of 0.1 km of horizontal resolution)
Wind flow models	Linearized flow models
Needed input meteo data set	From one surface station (or one profile of temperature, wind speed and direction) representative for the upstream wind flow
Terrain pre-processor	Topography and roughness length
Validity of flow	Local scale, on upstream side and on top of the hill for neutral to slightly stable and uniform incoming wind
Meteorological study needed	- Basic description of the dispersion climatology, including representativeness of the meteorological data - Search for adverse dispersion conditions and check on their wind simulation (analogous case studies, conceptual models,...)
Special problems	Flow not valid where wake and separation occur
Computer and data management requirements	Small (PC)
Needed level of expertise	A basic understanding of boundary layer flows and of computer models
Remarks	The choice of the model has to be duly justified and documented
Dispersion models	New generation dispersion models (Lagrangian or Eulerian)

5.4 Single low hill of moderate slope

Regulatory dispersion calculations often have to face the problem of one first topographical obstacle, hill or slope, where high pollutant concentrations can be expected by impingement and recirculation processes. In case of a single low hill with moderate slope, Table 6 applies.

5.5 Single simple large valley

A meteorological screening analysis should enable one to decide if the plume(s) can be trapped into significant 3-D circulations across the valley and near its slopes. Diurnal cycle of measured wind speed and direction as well as a basic meteorological expertise represent valuable tools. Then, their possible influence on the dispersion calculations (e.g. fumigation during wind reversal) has to be evaluated before deciding to include or neglect them. For plumes emitted in the centre of large valleys, the problem can be sometimes reduced to the simplest case Table 4, where the vertical wind profiles should be adapted). Otherwise, Table 5 applies.

5.6 Hilly terrain

In some simple cases, Table 4 can be applied. Otherwise Table 6.

Table 7 : Wind flow models for very complex terrain

Requirements on wind flow results	3-D or 4-D wind and turbulence with enough resolution to resolve the features of the circulations (0.1 to 1 km of horizontal resolution)
Wind flow models	Non-hydrostatic flow models (3-D or 4-D)
Needed input meteo data set	3-D initial and boundary conditions based on appropriate analysis schemes (nesting, nudging,...) and including temporal evolution for prognostic studies
Terrain pre-processor	Topography, land-use data and soil classification
Validity of flow	- Near-source, local and regional scale (in principle not limited)
Meteorological study needed	- 3-D description of the dispersion climatology, including diurnal and seasonal cycles, as well as analysis of representativeness of the input data (meteorological stations needed in the simulation domain) - Synoptic flow conditions influencing the different local circulations - Search for adverse dispersion conditions and check on their wind simulation (analogous case studies, conceptual models,...)
Special problems	- Initial and boundary conditions - Validation of resultant wind fields (e.g. wind in the stable boundary layer, oversmoothing)
Computer and data management requirements	Very high (powerful workstation or supercomputer: depending on the number of simulated cases)
Needed level of expertise	Up to now, use of such models is restricted to specialized scientists (high level of expertise in atmospheric science and computer technique)
Remarks	Still a scientific challenge
Dispersion models	New generation dispersion models (Lagrangian or Eulerian)

5.7 Complex terrain

Tables 5 or 7 apply, according to the importance of non-hydrostatic effects (Bernhardt, 1991). Model verification is still hampered by the lack of suitable experimental data.

5.8 Very complex terrain

This case corresponds to the following Table 7. Mass consistent models can also be used if they are based on a very comprehensive data set. Model verification is still hampered by the lack of suitable experimental data.

6. Summary and conclusions

In this report we have considered the problem of modelling the wind field over complex terrain in the frame of regulatory and non-regulatory pollutant dispersion calculations. A first analysis has been performed to single out the complex terrain flows that can effectively influence the atmospheric dispersion of pollutants. Different terrain classes have been defined in relation to terrain and flow complexity. The main features of mesoscale circulations that characterize each class have been delineated, and the kind of flow modelling appropriate to each case indicated.

The existing types of wind field models for complex terrain have been introduced. Only models that can be employed for application purposes have been considered. For each class of models a brief description of theoretical foundations, range of applicability, input data and computational requirements has been given. A few existing models have been cited and proper references have been given to applications performed during the recent years.

Until a short time ago atmospheric dispersion of pollutants over complex terrain was considered a research matter due to the huge computational power required by flow models and their intrinsic complexity. The fast progress of computer technology now makes feasible the use of prognostic flow models for application purposes. In the meantime, the development of mesoscale modelling has also enlarged the range of possible application, giving the models much more flexibility. The simpler diagnostic wind field models (like linearized and mass-consistent models) can now be applied over long time periods and can be used for real-time computation, e.g. inside industrial plants pollution control networks. The modelling tools now available improve the dispersion calculations over complex terrain and overcome the limitation of traditional Gaussian-type dispersion models based on the hypothesis of wind field homogeneity and stationarity.

Even if many flow models for application purposes are now available, wind field modelling over complex terrain remains a matter for experienced users and cannot be applied routinely. Verification is still hampered by the lack of suitable experimental data. The choice of the model to be used and of the type of simulations to be performed has to be taken by experienced meteorologists. Almost no specific guidelines for wind field modelling are presently available. The first operation should be a survey of the site topography, land-use and climatology. This analysis should help to decide if wind field modelling is effectively necessary and to determine which classes of models are applicable in the given situation. The choice of model has to be conditioned also by the input data availability (e.g.: objective analysis model can be successfully applied only if the needed measurements are available). The degree of complexity of topography has to be considered when selecting the scale and space resolution of the simulations. Local climatology and synoptic conditions should be considered in defining initial and boundary conditions for the simulation. Experience is also needed for analysing model results.

Atmospheric flow over complex terrain is still far from being completely understood. Many aspects of the matter are still the object of research activities: e.g. surface fluxes and turbulence modification induced by complex terrain, vegetation cover effects, etc...

This report can hopefully be a foundation for the construction of European guidelines for wind field modelling over complex terrain.

7. Recommendations

The following sections focus on a few selected topics. They are not really dedicated to the practical use of these models and are far from comprehensive. They primarily represent needs of the modelling community towards research, improvements and to access to input data.

7.1 Research and model improvements

Intensive research activity related to different aspects of wind field and dispersion modelling over complex terrain is still needed.

An important topic for harmonization purposes is the adequate evaluation and validation of atmospheric flow models, including a better assessment of the uncertainty of their results. Efforts are still needed within the framework of international research programmes to select or develop experimental data sets which can be suitable for wind field model evaluation over complex terrain and to define benchmark criteria and exercises. Verification is still hampered by the lack of suitable experimental data. Neither a review of existing data sets nor any experiment has been performed within our working group 4 of COST 710. Anyway, according to our knowledge, the existing experimental data sets are often incomplete and lacking of information mainly because they have been usually programmed for scopes different from complex terrain flow and dispersion model validation. A huge amount of work is generally needed just to clean, validate the data and make them finally suitable for model evaluation.

Wind field models over complex terrain listed in this report are mainly research-born or research-oriented models, although they have been used for practical air pollution applications. Efforts should also be devoted towards applications, in terms of code portability, technical documentation, user's guides and recommendations. Only a few models have reached the status of guideline pre-processing models (VDI, 1992b), partly because the upgrade from rather simple and crude models to the new generation complex wind field models is a challenge for scientists, policy makers and users. Therefore cooperative implementation programmes involving them all are needed.

An obstacle to the diffusion of flow modelling use is often the lack of culture regarding atmospheric flow and pollutant dispersion, but another important reason is the difficulty to access proper input data, as e.g. meteorological data (see chapter 7.3).

An important need for improvement exists in the field of integration between atmospheric flow models and soil and vegetation models. Satisfactory flow modelling is in fact strongly conditioned by a proper description of the bottom boundary conditions and their evolution. The possibility to model surface effects is of course strongly tied to the availability of the needed terrain description (see chapter 7.2).

At last a relevant topic that needs to be investigated is the structure and evolution of turbulence over complex terrain, the comprehension and knowledge of which is still very poor. Related to this issue is the structure of the planetary boundary layer, particularly in relation to the parameterization of the nocturnal stable boundary layer (see chapter 4.3). We do not have enough verification experiments in order to show whether non-hydrostatic prognostic and mass-consistent diagnostic dispersion models can be applied over complex terrain for regulatory purposes with confidence now.

7.2 Access to orographic and physiographic data

Detailed orographic and physiographic data are needed for wind flow modelling over complex terrain, but they do not always exist at sufficient resolution. Fortunately, different programmes have addressed this question and data sets for many parts of the world with a rather good resolution can now be downloaded through Internet web servers. Improvements still remain necessary, especially for very high resolution data and multinational studies. National topographic agencies should be asked. Hereafter we give a couple of addresses of institutions delivering data sets from many parts of the globe (not always free of charge):

- NGDC = National Geophysical Data Center, USA, Information: http://www.ngdc.noaa.gov, look "solid earth geophysics" and then "topography": GLOBE, Global Land One km Base Elevation (correctly: 30 seconds resolution). Data can be directly downloaded from the following internet address: edcwww.cr.usgs.gov/landdaac/gtopo30/gtopo30.html.
- USGS = U.S. Geophysical Survey also producing a global land cover data-set (edcwww.cr.usgs.gov/landdaac).
- NOAA = National Oceanic and Atmospheric Administration provides vegetation data with a 10 min resolution covering the entire globe.
- A European land cover database is being produced within a project called CORINE (European Environmental Agency).
- RIVM=National Institute for Public Health and Environmental Protection (NL), provides a 10 minutes Pan-European land-use database. A CD-ROM is available asking directly to the Institute (For information: R.J. Van De Velde RIVM, P.O. Box 1, 3720 BA Bilthoven, The Netherlands, lbgrob@rivm.nl).

We are not aware of other institutions distributing Europe-wide orographic or physiographic data sets. We think that an effort should be made to produce high resolution orography, soil type, and land cover data available on the European scale on a common base. Presently those kind of data are often treated in a different way by each national agency (different projection, classification, resolution).

7.3 Access to meteorological data

In more detail, we hereafter address the question of data access from the National Weather Services (NWS). NWS play an important role in the harmonization within the field of meteorological pre-processing. Actually, they represent the main meteorological data suppliers and have practised harmonization within their measurement and communication networks for a long time. Nevertheless, in some countries, the environmental community has some difficulty with access to observations and gridded data. The following recommendations are issued to promote improvements where needed. On the other hand, it should be noted that such data rarely belong to the basic products of NWS and can only be made available under an appropriate charge, due to their high production cost and to increased financial pressure on the NWS.

Hence, the access to checked data sets (1 to several years) from surface stations (e.g SYNOP observations, but preferably automatic stations) and upper air soundings (TEMP’s and full resolution) of the European NWS should be improved where administrative restrictions inhibit this access.

An increasing number of NWS run so-called Local Area weather prediction Models (LAM) on an operational basis, with a mesh size ranging from 10 to 30 km. Most of them are hydrostatic models. In the near future, non-hydrostatic models will be put in operation (LM: Germany, possibly the non-hydrostatic version of ARPEGE/ALADIN: France, see Steppeler, 1996, Bubnova et al., 1995, Lahore et al., 1996), with mesh size below 5 km. Their initialization with input meteorological data will also benefit from new research, introducing 3-D and Four Dimensional Data Assimilation (FDDA) with nudging techniques, improving noticeably their ability to resolve small scale features. Although their results have been in the past mainly confined to short term weather predictions, they have recently been increasingly used for wind field prediction, trajectory and dispersion calculations on regional scales. In the planetary boundary layer (PBL), they still exhibit weaknesses over complex terrain, firstly because they use the same PBL-parameterization at all grid points, regardless of the local topography, secondly because they do not use enough resolved input data. Nevertheless, their strengths compared to a lot of PBL-models are numerous:

- they reproduce the synoptic forcing well,
- they include moist convections, clouds and precipitations,
- they are running on an operational basis,
- their initialization is based on numerous measurements and observations,
- they are undergoing a continuous verification process, leading to improvements,
- their produce hourly predictions (full diurnal cycle),
- they predict the regional wind field rather well where the topography is resolved by their mesh size,
- their results can be efficiently used as initial and boundary conditions for smaller scale nested models.

Due to the tremendous amount of data produced, the full data sets are restricted to real-time wind/trajectory predictions and dispersion calculations. Only limited data sets are presently archived for statistical applications at the NWS running such LAMs. We recommend therefore that archive and retrieval procedures be further developed so as to make them more widely available for the smaller scale wind field models. Adequate sets of representative weather situations with the corresponding numerical data products could also be prepared by the NWS.

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