Meteorology

COST Action 710 Final Report

Harmonization in the Preprocessing of Meteorological Data for Atmospheric Dispersion Models

Introduction

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1. Overview

1.1 Background to Project

The objective of the project described in this volume, is to improve both the quality of the meteorological data used in air pollution calculations and the ways in which such data is used. The project was carried out between 1994 and 1997 as part of "European Co-operation in the field of Scientific and Technical Research" (or COST), under COST Action 710 with the somewhat formidable title "Harmonization in the Pre-processing of Meteorological Data for Atmospheric Dispersion Models". COST is a framework for co-operation between European countries through projects, or so-called "actions", which are not part of European Union research programmes. COST also provides European countries that are not members of the European Union with the opportunity to participate in European programmes. There are COST projects in the following areas: informatics, telecommunications, transport, oceanography, materials, environment, meteorology, agriculture and biotechnology, food technology, social sciences, medical research, civil engineering, chemistry and forestry.

The purpose of this introduction is to explain the importance of studies to improve knowledge in this somewhat neglected area, to outline the background to the project and to provide a summary of the work carried out and the results achieved. COST Action 710 is one of a number of current COST projects in the field of meteorology and the only one directly concerned with air pollution. Within COST there is another Action (COST 615) under environment, concerned with the application of air pollution models to the improvement of air quality within cities, as part of the so-called COST CITAIR programme. Although not managed together, the studies under COST 710 will feed into developments under COST 615.

Dispersion models often require meteorological inputs which are not routinely measured, such as surface heat flux or boundary layer depth (or mixing depth), which have to be inferred from other measurements. These quantities need to be estimated before the dispersion calculation can be performed. There are also other quantities, such as wind speed and direction, which although routinely measured may not be available at the locations required for the dispersion calculation. Normally data from a nearby site representative of the location is used, but the inaccuracy involved has not been quantified. Estimating the representativeness of point measurements was considered very difficult and was not addressed in the project. A method for obtaining representative wind fields over Europe is discussed later in Section 2.9.

When dispersion climatologies are applied, the meteorological data at a site needs to be processed to provide a climatological description of the dispersion characteristics of the site. This can be done in various ways; for example by using several years of observations as input to the dispersion model, or by statistically processing the data prior to running the model in order to reduce the number of dispersion calculations needed. The estimation of unmeasured meteorological parameters and the climatological processing of data are often referred to as the "pre-processing of meteorological data" and are the issues with which COST 710 is concerned.

As more advanced air pollution models are developed, the descriptions of meteorology underlying the calculations tend to become more sophisticated. As a result the establishment of effective and reliable ways of performing the meteorological "pre-processing" becomes even more important if the models are to fulfil their potential. Because environmental considerations have a significant role to play in the siting of industrial plants, it is also appropriate that some consistency in the approaches used in different European countries is encouraged. Within the project the view prevailed that such "harmonization" was best promoted by seeking consensus on what constitutes best practice and then encouraging convergence towards this. This approach has the advantage of being non-prescriptive, and hence not acting as an obstacle to the introduction of improved techniques in the future. By testing widely used methods of pre-processing the meteorological input data required by air pollution models, this co-operative study aims to encourage improvements and harmonization.
The original motivation behind the establishment of COST Action 710 can be traced back to the first workshop[1] in a series promoted by the "Initiative on harmonization within atmospheric dispersion modelling for regulatory purposes". One of the recommendations to emerge from this workshop was that "there should be an action for harmonization of meteorological input for new-generation (dispersion) models". The Memorandum of Understanding for the Action was approved by the COST Senior Officials in February 1994 and the Action got under way with the first management committee meeting in April 1994. The technical content of work listed in the Memorandum of Understanding is reproduced as Appendix A1. As a result of a questionnaire distributed to participants it was decided that the bulk of the work carried out under the project could be effectively co-ordinated by setting up four Working Groups to study: (1) the surface energy balance, (2) mixing height determination for dispersion modelling, (3) vertical profiles of wind, temperature and turbulence, and (4) wind flow models over complex terrain for dispersion calculations. The results of each Working Group report are presented as separate sections in this volume.

The countries participating in the project are: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Hungary, Italy, The Netherlands, Portugal, Slovenia, Spain, Sweden, Switzerland, and the United Kingdom. Much of the work was presented at the Fourth Workshop on Harmonization within Atmospheric Dispersion Modelling for Regulatory Purposes, held in Ostend, Belgium, 6-9 May 1996, papers from which will be published in a special volume of the International Journal of Environment and Pollution (see Appendix A2). It is apparent that much research remains to be done on this neglected aspect of dispersion modelling if complete harmonization of predictive methods is to take place. The COST 710 programme finished in April 1997 and this volume is a report on COST 710 activities in order to disseminate information to a wider audience. If the publication of this volume encourages and promotes further interest in the meteorology underlying air pollution studies then it will be considered a success.

COST 710 has not specifically addressed ways in which the harmonization of pre-processing of meteorological data for atmospheric dispersion models would be different when dealing with urban air pollution problems, although this is a very important issue in European air pollution policy. This will be considered in a proposed new COST Action,

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[1]Proceedings of the Workshop: Objectives for Next Generation of Practical Short-range Atmospheric Dispersion Models, May 6-8 1992, Risø, Denmark edited by H R Olesen and T Mikkelsen, NERI, P O Box 358 DK-4000 Roskilde Denmark (ISBN 87-550-1836-X).

which is under consideration at present. This new COST Action 715 has the provisional title "Meteorology applied to Urban Air Pollution Problems".

1.2 Dispersion Modelling and Regulatory Applications

Dispersion modelling is the technique widely used over the past 40 years to estimate the mixing and dilution of pollution in the atmosphere. It concerns itself mainly with dispersion in the atmospheric boundary layer, which is that portion of the atmosphere where the direct effect of the surface (on heat, moisture, wind profiles etc) is felt as a consequence of turbulent transfer.

In the report of Working Group 3, Figure 2 shows schematically the dispersion in the atmosphere of pollution released from a chimney. Most attention to modelling this behaviour centres on describing in mathematical equations the spread of airborne material as a function of downwind distance. This is shown in an idealised way in Figure 3 of the Working Group 3 report, where the shape of the dispersing plume is assumed to have the form of a Gaussian or bell-shaped function, examples of which are drawn on the diagram. The application of short-range regulatory models in flat terrain is illustrated by these figures. COST 710 was not only interested in this situation but was also concerned with the meteorology required for dispersion modelling in more complex terrain and over longer ranges.

The properties of turbulence cannot be explicitly determined from first principles since the basic nature of turbulence involves a range of scales of motion which are coupled together making solution by even the most powerful computers an impossible task. The problem is particularly difficult in the case of the atmospheric boundary layer which is subject to continual variation in time and space. In the context of regulations dealing with the planning, control and management of atmospheric pollution, there is a need to have available suitable, practical models, so-called "regulatory models", which can be readily applied following well documented procedures.

In designing regulatory models of dispersion out to 30km or so from a source, the usual approach adopted is to characterise the atmospheric boundary layer in terms of a few main parameters and to use a combination of empirical data and theoretical ideas to determine the dispersion for each combination of parameter values, or for a number of "classes" of parameter values. The most important parameters determining the dispersion properties of the boundary layer concern the stability of the boundary layer, which can broadly classified as unstable, neutral or stable (see for example Figure 1 of the report of Working Group 3).

There is a significant difference between the traditional and more recent approaches to the way stability is described. The traditional approach following the work of Pasquill[2] of the early 1960's is to classify the stability in terms of a few (normally 6 or 7) "stability categories". In each stability category the detailed conditions (such as the sky conditions, the wind speed, the vertical temperature profile, the turbulence levels and the surface radiation budget) will vary, but the categories aim to differentiate the broad differences in dispersive behaviour. Plume spread is modelled as depending only on downwind distance

[2]Pasquill F, 1961, The estimation of the dispersion of windborne material, Met Mag, **90**, 33-49

and the stability category. These stability categories form the basis for describing dispersion in many commonly used regulatory models.
More recent years have seen the development of dispersion models based on an approach which is closer to the methods commonly used for describing the flow in the atmospheric boundary layer (and indeed for describing the flow in turbulent boundary layers generally, such as in engineering flows). Such models attempt to describe the dispersion in terms of the same few fundamental parameters as are used to characterise the flow, such as wind speed, surface heat flux and boundary layer depth.

This approach has a number of advantages over simple classification schemes. The dispersion can be related directly back to basic physical parameters, such as wind speed or the heating or cooling of the air at the surface. These parameters are in turn an essential part of larger scale numerical weather prediction models. The approach also allows the meteorology of dispersion to be described in similar terms for cases involving differing spatial scales, such as emissions from tall stacks, emissions from short stacks, dispersion over short distances out to 30km and dispersion over longer distances. The simple Pasquill stability category approach does not provide a means for treating the variation of turbulence and dispersion with height, and is most applicable to near ground-level sources over short distances. Over longer travel distances the variation of meteorological conditions in space and time becomes of increasing importance to the description of dispersion. The use of a framework based on fundamental boundary layer parameters still applies to longer range transport, albeit that the fundamental parameters are varying in space and time, and the atmospheric boundary layer may be transformed between different states of equilibrium.

For regulatory purposes dispersion models are applied in broadly two principal ways. Sequential, usually hourly, meteorological data is entered into the model and a time series of hourly average predicted concentrations is obtained. These may be used to obtain peak concentrations over a range of meteorological conditions or some statistical average, such as the mean or the 98 percentile, by processing the model's results. Alternatively a climatology is used as input data to the model. This contains a limited number of categories of meteorological conditions and the frequency with which they occur. By running the model over these categories and taking a weighted average according to the relative frequency with which each occurs, the mean concentration may be obtained in a way that is computationally efficient. The same quantity can be estimated by running a year or more of sequential data. This will avoid the error introduced by the discrete categories but the calculation is more laborious.

1.3 The Need for Harmonization

The role of dispersion modelling has expanded in recent years from an activity only practised by experts, as a result of the added interest of engineers in a tool to help them choose a chimney height or design new commercial or industrial developments. At the same time there is a need for objective, reliable and comparable information at the European level on the state of the environment, to enable policy makers to take the appropriate measures to protect the environment. Air quality modelling has a special role for Member States of the European Union and others, with respect to projects likely to have significant transboundary effects. Unless the Member States use harmonized models, readily accepted on both sides of the border, there is likely to be considerable difficulty.

The European Directive 96/62/EC on Ambient Air Quality Assessment and Management has now been adopted. This Directive lays down common criteria and requires common reference techniques for air quality modelling. Recent developments reported at Workshops on Harmonization within Atmospheric Dispersion Modelling have provided data sets on which to test models and common measures for judging model performance. Three data sets from Kincaid, Copenhagen and Lillestrøm were discussed at the first three Workshops on Harmonization within Atmospheric Dispersion Modelling, and were supplemented at the Fourth Workshop in Ostend in 1996 (see above), by the addition of data sets from Indianapolis (84m stack in a town) and Bull Run (a power plant with a 244m stack in moderately complex terrain).

1.4 Preprocessing of Meteorological Data

For the routine application of dispersion models a user expects data sets of meteorological data to be provided in a form that can be used with the dispersion model the user has chosen to apply. The purpose of the COST 710 programme is to address the accuracy of meteorological data which dispersion models use, to ensure that the most appropriate meteorological data is used in dispersion calculations. Routine meteorological parameters do not provide directly all the necessary meteorological variables to determine dispersion conditions even near the surface of the ground. Involved calculations and interpolation of data from routine meteorological stations may be necessary. In addition statistics on the frequency of occurrence of each variable is needed for entry into some of the dispersion models, while other dispersion models require time series of the meteorological variables.

Pre-processing is the activity of inferring meteorological parameters needed in dispersion models using routinely available meteorological data, as well as the way in which time series of hourly data over long time periods are summarized to produce climatologies of dispersion categories. Possible errors and differences between methods used in this pre-processing can be of comparable or even greater importance to errors occurring in the dispersion modelling itself. It is essential that there is consistency in the way in which meteorological input parameters are defined and used if the results of dispersion models are to be compared in a meaningful way.

The bulk of the work undertaken by COST 710 has been divided up between the four Working Groups. The fundamental parameters which determine the structure of the atmospheric boundary layer and the difficulties of obtaining reliable values for application to dispersion models provide the motivation for the choice of work programme chosen by the Working Groups. The Working Groups formed considered the following subjects:

(1) the surface energy balance. The surface heat flux is a key parameter in determining dispersion characteristics, but it is not usually measured routinely. Reliable methods for determining the surface heat flux for use in dispersion modelling was the main topic of Working Group 1.

(2) mixing height determination for dispersion modelling. There are various ways of defining the mixing height, which in Working Group 2 of COST 710 was taken to be "the depth to which pollution will disperse within a time scale of about an hour". Working Group 2 reviewed the wide range of available methods for estimating mixing height and carried out comparisons with data.

(3) vertical profiles of wind, temperature and turbulence. A number of formulae were identified for describing the vertical profiles of wind speed, temperature and turbulence in the lower atmosphere. The work of Working Group 3 was to review these various formulae and to compare them against some data sets of reliable measurements.

(4) wind flow models over complex terrain for dispersion calculations. In situations of sufficiently complex terrain one can no longer assume uniform flow conditions and dispersion conditions. Complex terrain models have been developed to address these situations. These models include linear flow models, mass consistent models and dynamic models which attempt to describe the evolution of flow and turbulence. They are necessarily complex. Defining the flow field was the main focus of Working Group 4 who attempted to give general guidance on situations when such models are useful.

Research was also undertaken on the sensitivity of dispersion modelling results to the way in which climatologies are described but this was not conducted within a separate Working Group (see Section 2.8). In particular, the sensitivity of dispersion calculations to the number of years of data used and how it is processed e.g. time series or statistical summaries, has been assessed.

Current practice in each topic area was reviewed using the knowledge of experts in the field, literature surveys and questionnaires. This revealed a number of standard methods in routine use in participating countries. These need to take account of local situations e.g. methods developed and tested in the Netherlands and Denmark for determining the surface heat balance may not work so well when applied to the far north of Europe. Data sets collected during intensive meteorological measurement programmes have also been identified during the initial phase of the programme and were used to test the application of the schemes.

Membership of the Working Groups is listed in Appendix A3. The main outcome of COST 710 is set of recommendations in respect of the schemes for determining meteorological input parameters in dispersion models. This should reduce one potential source of deviation between the predictions of dispersion models.

2. Relationship between Topics in COST 710

2.1 Fundamental Parameters of the Turbulent Atmospheric Boundary Layer

It is clear that the description of dispersion is dependent on the properties of the atmospheric boundary layer. The basic properties of the boundary layer that are of importance for air pollution studies are the wind profile (wind speed and direction) which determines transport, the level of turbulence which is responsible for the spread and dilution of plumes and the height of the boundary layer. The temperature profile affects the rise of plumes and the level of turbulence.

The properties of the atmospheric boundary layer are primarily derived from experimental data, analysed within a theoretical framework consisting mainly of similarity relations. The levels of turbulence in an atmospheric boundary layer with zero heat flux at the surface in uniform, homogeneous, steady conditions are determined by the following fundamental parameters: (1) the velocity at the top of the layer (or the geostrophic wind speed G), (2) the Coriolis parameter f arising from the Earth's rotation, and (3) the roughness of the surface described by the roughness length z_0 , a measure of the height of typical surface irregularities. One may also consider the background thermal stratification of the atmosphere described by the Brunt-Väisälä frequency of the layer above the mixing layer. The Brunt-Väisälä frequency is defined by the square root of the product of the buoyancy parameter and the vertical potential temperature gradient (see the Working Group 2 report). In boundary layer meteorology properties of the boundary layer, such as the wind, temperature and turbulence profiles are expressed as functions of the height above ground usually in a non-dimensional form involving scaling of fundamental parameters. The shape of the profiles is determined from observations.

It turns out that it is not always possible to classify actual observations of neutral atmospheric boundary layers in terms of these few basic parameters. In practice the assumption of steadiness is often poor and the boundary layer does not reach its equilibrium depth. Hence the boundary layer depth h is not completely fixed by the geostrophic wind speed G, Coriolis parameter f and z_0 , and h should be regarded as an extra parameter needed to describe the boundary layer. For a given geostrophic wind speed, Coriolis parameter, roughness length and boundary depth, turbulence levels tend to adjust relatively quickly and so can often be regarded as determined by these four fundamental parameters. Near the surface, turbulence levels are more closely related to the friction velocity u_* , describing the transfer of horizontal momentum to the surface, than the geostrophic wind speed G. It is more useful near the surface to scale the wind profile and turbulent velocities with respect to u_* and the friction velocity becomes a further fundamental parameter which can be used as an alternative to G.

When the surface heating is non-zero, the surface heat flux H is the other driving force setting up the structure of the boundary layer. During the day, when the flux of heat carried from the surface into the atmosphere by convection is usually positive, the heat flux acts as an extra source of turbulence over and above that caused by the wind. At night the heat flux is usually negative and this tends to drain energy down from the wind induced turbulence, leading to much reduced turbulence levels for a given wind speed. Since the interests of boundary layer meteorology and dispersion modelling are in the main velocity and length scales, it is usual to introduce a new length scale L_* into the equations describing wind, temperature and turbulence profiles. L_* is the Monin-Obukhov length, equal to u_*^3/H apart from some constant of proportionality. In convective boundary layers it is usual to introduce the convective velocity scale w_* which is proportional to $(hH)^{1/3}$.

In summary we are led to a picture in which, for relatively ideal conditions, boundary layer turbulence is determined by the values of a few fundamental parameters, namely the geostrophic windspeed G or the friction velocity u_* , the Coriolis parameter f, the roughness length, z_0 , the surface heat flux H, and the boundary layer depth h, or convenient combinations of some of these parameters (such as L_* and w_*). It will be readily apparent that these fundamental parameters occur frequently in the formulae listed in the reports of Working Groups 1, 2 and 3.

If these parameters are to be useful for descriptions of turbulent dispersion in a practical way, they must be available at any site. This is a necessary preliminary before using these parameters to describe the dispersion of a passive non-reacting chemical in the atmosphere. The Coriolis parameter f is fixed by the latitude of the site and the roughness length z_0 is fixed by the nature of the surface at the site of interest. The geostrophic wind speed G is determined by synoptic meteorology on a regular basis at any location. Estimates of the friction velocity u_* can also be made routinely from the wind and temperature measurements near the ground at a nearby site provided a representative value of z_0 is known. The Working Group 1 report describes in detail how properties of the atmospheric surface layer may be derived from near surface measurements.

The direct measurement of the surface heat flux H requires sophisticated instrumentation and therefore H cannot normally be directly obtained from measurements. Processing of routinely measured data is required. As reviewed in the report of Working Group 1 a number of different methods have been proposed and used to determine the surface heat flux on a routine basis. Similarly at most locations measurements of the mixing layer depth h are not available, except when sophisticated equipment is available and even then interpretation may be difficult. A very large number of formulae and methods have been proposed for determining h and these have been comprehensively reviewed in the Working Group 2 report. Since instead of being measured directly, the surface heat flux and the mixing height must be derived from other readily available meteorological parameters using formulae, a major part of the COST 710 project has been on testing methods for the routine determination of surface heat flux and mixing height and this is contained in the work reported by Working Groups 1 and 2. The aim has been to test current methods and not to develop new ones. Surface heat flux and mixing depth are the two fundamental parameters for which the literature contains the widest diversity of formulae, so that a high priority in COST 710 has been given to attempts to recommend methods for estimating these parameters. Particular attention has been paid to identifying and using recent databases of relevance to these studies.

Measurements of wind, temperature and turbulence are not normally measured at heights much above 10m above ground on a routine basis. Hence the description of turbulence throughout the boundary layer relies on formulae which include the height dependence of these quantities up to the mixing height. A number of formulae for the profiles of wind, temperature and turbulence have been proposed in the literature, although the literature does not contain a large number of alternative formulae. These formulae consist of empirically determined relationships between the required quantities and the fundamental parameters and are normally expressed in non-dimensional form. The report of Working Group 3 has been directed at testing such formulae. No attempt has been made to develop new methods. Because more recent methods of calculating dispersion place emphasis on the way in which dispersion varies with height in the boundary layer, the height dependence of the wind, temperature and turbulence was given high priority in COST 710. Use was made of recent sets of observations which could be used to test formulae.

Estimates of dispersion are frequently required at sites for which no routine meteorological data set exists from which turbulence can be estimated. In low-land areas, with broadly flat homogenous terrain, it is normally possible to use a nearby site or interpolate between sites at which a long series of observations have been made. In regions of complex terrain this is no longer possible and Working Group 4 were faced with tackling the formidable problems of dispersion in complex terrain where the simple theories of the boundary layer based on a few fundamental parameters no longer apply. In such terrain the wind flow may no longer be interpolated directly from the available observational network or from the synoptic wind field. Dispersion in complex terrain is most sensitive to the wind flow, because the wind field determines where the pollution cloud will travel. Hence Working Group 4 considered methods for estimating wind fields in complex terrain as the issue of highest priority. The other aspects of the atmospheric boundary layer are not considered in detail. However the Working Group's report does contain guidance on how the question of dispersion in complex terrain should be tackled.

2.2 Dispersion Models

Many kinds of dispersion model have been developed to describe the way in which a passive, non-reacting chemical mixes within the atmosphere. The process that controls the mixing is atmospheric turbulence so that all models implicitly or explicitly require information on turbulence levels in the atmosphere under various meteorological conditions, if they are to be applied in a practical way. The models also require information about the air flow carrying pollution away from the point at which it is released. Depending on its sophistication the successful use of a model will require greater or lesser information about the turbulence levels. The COST 710 project has sought to harmonize ways of determining the key parameters describing turbulence. It is accepted that some models may require more complex parameter values which have only been considered briefly in Working Group reports. For example Lagrangian particle flow models require profiles of the Lagrangian time scale. Estimates of the Lagrangian time scale amount in effect to making estimates of the size of turbulent eddies and this is briefly discussed in the report of Working Group 3. Similarly Eulerian grid models generally require eddy diffusivities which depend on turbulence levels and eddy size. These are also discussed in the report of Working Group 3.

All dispersion models are dependent directly or indirectly on the vertical and horizontal spread of plumes which can be described by dispersion parameters or in some cases by vertical or horizontal eddy diffusivities. The dispersion parameters or eddy diffusivities are empirical functions of the fundamental parameters, in a similar way to the wind, temperature and turbulence profiles. The close connection between the dispersion of material and the dispersion of heat and momentum should not be forgotten. The review of dispersion models was not considered part of the COST 710 programme. However dispersion models which directly or indirectly make use of dispersion parameters, or profiles of eddy diffusivities, which are consistent with the most appropriate description of the atmospheric boundary layer, are to be preferred.

For short-range dispersion the air flow and dispersion characteristics (or turbulence levels) are generally assumed to be the same throughout the area of interest and over the duration of travel from source to receptor. Fluctuations in wind over whatever averaging time is assumed within the model are generally treated as part of the turbulence and would be included in any estimation of turbulence intensities. Generally an averaging time of about 1 hour is adopted in dispersion models. The "traditional" approach to dispersion modelling, using a classification of dispersion categories, assumes that all information about different levels of turbulence has been incorporated within the differences between the dispersion categories. Each category is associated with a different variation in plume spread with downwind distance, but in each case the functional dependence in the crosswind and vertical directions follows a Gaussian form. This concentration distribution has been chosen for mathematical convenience and because it is thought to broadly describe the shape of the pollution concentration in a plume.

It is always possible in principle to relate specific meteorological conditions to a traditional "Pasquill stability" category. However the same dispersion category may arise for different combinations of surface heat flux and geostrophic wind. It is often the relative importance of wind speed and heat flux in producing turbulence which is important, rather than the absolute size of each. This is because if the wind speed is increased and the heat flux is also increased in magnitude, then the turbulent velocities can remain proportional to the wind speed. As a result, although the plume spreads faster in time, it also travels downwind faster and can have a similar width at a given downwind distance. This relative importance can be characterized quantitatively via the Monin-Obukhov length, L_* , defined and used by Working Groups 1, 2 and 3, or by the so-called Richardson number. These effects are not quantitatively represented in the use of the "Pasquill stability" category, although most stability category definitions reflect this qualitatively. Although some traditional dispersion models make allowance for surface roughness, and most treat the mixing height as a limit to vertical dispersion, they do not generally allow for the full effect of changing roughness length, mixing height and source height.

Models based on "Pasquill stability" categories are restricted in their treatment of factors that can influence plume spread. In contrast models, which rely on describing plume spread in terms of the fundamental parameters, should in principle encompass a fuller description of the dependence of plume spread on atmospheric conditions.

The general approach to describing atmospheric turbulence adopted in COST 710 is the one widely, if not universally, followed. Hence regardless of the details of their structure all recently developed dispersion models rely directly or indirectly on the parameters discussed within the Working Group reports. One of the purposes of COST 710 is to raise awareness of the differences in prediction that can arise because of the differences in the methods for calculating the fundamental parameters describing turbulence profiles. This is an aspect of dispersion modelling which is largely neglected and is independent of differences in the dispersion models themselves.

Dispersion models should ideally take into account the differences in turbulence levels at different heights in the atmosphere. Working Group 3 have concentrated on turbulent profiles through the atmospheric boundary layer. In practical applications the turbulence profile dependence on height above ground has to be known before a model can be applied. Working Group 2 also discusses atmospheric profiles since the development of the boundary layer leading to changes in mixing height is closely linked to profiles within and above the boundary layer. One may also wish to evaluate a mixing height from a measured profile. Working Group 1 touches on profiles but largely in connection with profiles near the surface where they interact with the surface energy balance.

Working Group 4 does not consider the structure of the atmospheric boundary layer in complex terrain but directs attention to models which describe the wind flow. Wind field modelling is considered of more fundamental importance than the model of dispersion. Wind speed and direction are the fundamental parameters in this situation!

2.3 Limits to Dispersion Modelling

It should be recognised that the methods used to determine surface heat flux, mixing height and turbulent profiles from readily measured parameters are themselves based on models. These are often analogous to dispersion models but involve the dispersion of momentum, heat or water vapour rather than pollution. Formulae describing the turbulent transport of heat and momentum are implicitly applied in dispersion modelling.

One of the recurring themes of the reports of Working Groups 1, 2 and 3 is the use of empirical data, using scaling quantities to make combinations of parameters non-dimensional, and applying conservation laws to describe the structure of atmospheric turbulence. It is therefore not surprising that a choice of formulae for some quantities is available with no clear preferred formula. This choice of formulae should not be regarded as a weakness of the work presented but rather a realistic appraisal of the state of current knowledge.

In the real world the atmospheric boundary layer is never really steady; it is always subject to time variations caused by disturbances such as cumulonimbus clouds, rain and weather systems etc. In addition there are always variations in space from changes at the surface in roughness, topography or large-scale air motions. Despite these difficulties attempts to summarise the turbulent properties of the boundary layer in terms of a few non-dimensional combinations of the fundamental parameters have been reasonably successful leading to descriptions of boundary layer profiles in terms of simple scaling laws. One would not expect boundary layers to exactly satisfy these laws because of the variability of boundary layers in space and time. However they do provide a framework for describing different kinds of turbulent boundary layers and through these to provide better ways of describing dispersion.

The usefulness of these scaling parameters decreases as the complexity of the flow increases (e.g. due to complex terrain, coastal effects, the rural-urban interface or baroclinicity). In such situations it can become impossible to represent the flow in terms of a few fundamental parameters, and in cases of very extreme terrain it is not clear that even the concept of the atmospheric boundary layer remains useful.

Situations involving dispersion over longer distances usually start to involve effects caused by changes in terrain. Therefore longer range transport shifts the emphasis to changes in atmospheric flow. It is therefore inevitable that the Working Group 4 Report has a greater emphasis on determining the wind flow. The assumption of uniformity in short-range dispersion models no longer applies to situations of complex wind flow.

Knowledge of the spatial variation of precipitation is fundamental for assessing wet deposition of pollution. However precipitation and its effect on the structure of the atmospheric boundary layer was not a topic included in the work programme of COST 710.

2.4 Surface Energy Balance (Topic of Working Group 1)

For practical use, dispersion calculations need to be made in all kinds of situations. As discussed above in most cases a meteorological data set is not available at a particular site. Formulae and algorithms based on routinely available meteorological data must be used: the process known as parametrization, widely applied in air pollution modelling and boundary layer meteorology. These parametrizations generally involve using similarity theory to describe wind and temperature profiles near the surface and applying an energy balance at the surface using assumptions regarding empirically derived parameter values which may only apply in certain ideal conditions.

Estimates of the wind speed are available directly from routine measurements. However the thermal properties of the boundary layer are not routinely directly measured although they strongly influence the dispersion. Working Group 1 concerned itself with the main fundamental parameter influencing the thermal stability, the surface sensible heat flux, although this means looking at other near surface properties, such as the friction velocity and the Monin-Obukhov length as well. Two well established methods were compared in mid-latitude situations. Particular attention was paid to the surface heat balance at high latitudes, where the determination of the surface heat flux is a severe test of the suitability of the schemes. It appears that the methods need to be modified for extreme conditions. Calculated heat fluxes were lower than measured heat fluxes and furthermore there was disagreement between the two methods.

In another comparison for mid-latitudes it was shown that one of the established methods gives as good agreement with measurements of heat flux as a method based on measurements of the wind and temperature profile, although the latter would not be generally available. Finally ways of improving the parametrization of the surface energy balance, by describing the transfer of heat to the ground in more detail were considered. Usually methods rely on choosing an empirically derived constant and may be improved by a more flexible parametrization.

The use of numerical weather prediction models as an alternative way of obtaining suitable surface data for dispersion models was considered. Remote sensing using satellites is another approach to the problem.

From the surface heat flux and the wind speed the Pasquill stability class can be estimated. The distribution of Pasquill stability classes derived from the well established methods was considered. This revealed some serious discrepancies between the methods and in the comparisons with measurements at high latitude sites.

2.5 Mixing Height Determination for Dispersion Modelling (Topic of Working Group 2)

After dispersion category, the mixing layer height is the most important property of the atmospheric boundary layer required in dispersion calculations. Its definition is not straightforward. Working Group 2 have taken as a working definition that the mixing height is "the height of the layer adjacent to the ground over which pollutants or any constituents emitted within this layer or entrained into it, become vertically dispersed by convection or mechanical turbulence within a time-scale of about an hour". As in the case of the surface heat flux, determination of the mixing layer depth is dependent on formulae or algorithms describing parametrizations of properties of the atmospheric boundary layer.

A wide variety of remote sensing measurement techniques, such as sodar and in-situ measurement techniques, such as radiosondes, are available, leading to atmospheric profiles from which the mixing height can be estimated, but these measurement techniques are not generally routinely available. Instead a number of operational methods have been developed. In situations determined by mechanical turbulence these usually rely on formulae to describe the height of mixing. The height is an evolving quantity in situations driven by convective turbulence and the methods depend on solving equations describing the evolution of the boundary layer as heat is fed into it.

Although in-situ measurements are to be preferred when estimating mixing layer depth, for practical use methods based on simple computer models are generally applied. Working Group 2 have tried five methods for calculating the mixing height. The methods are based on similar principles with variations in choice of those parameters which are not measured or cannot be measured routinely. The Working Group have used three data sets to test the mixing height routines. The data sets come from fairly uniform terrain in the Netherlands, Switzerland and Germany and consist of a mixture of tower, remote sensing (sodar and electromagnetic profiler) and radiosonde data, together with measurements of turbulent fluxes at the surface. The intercomparison is further complicated because the measurement methods themselves give different results and need to be interpreted using models. The data consisted of a number of days on which the hourly evolution of the mixing height could be estimated from measurements.

Recommendations are made as to ways of estimating mixing height when profile data is available. When computer codes in meteorological preprocessors are used to calculate the mixing height from routine data, these should be designed in a way which allows for the substitution of measured or estimated values when appropriate. As these methods are by no means perfect, Working Group 2 suggest that these methods need further attention.

The Working Group 2 report also contains an extensive literature review, as well as an exhaustive list of the many equations used to parametrize the stable boundary layer height. These are generally in the form of explicit formulae. Choices of the prognostic equations describing the development of the convective boundary layer are also listed.

2.6 Vertical Profiles of Wind, Temperature and Turbulence (Topic of Working Group 3)

Working Group 3 have considered a number of formulae for describing the vertical profiles of wind speed, temperature and turbulence in the lower atmosphere. These formulae have often been developed for ideal conditions. Within Working Group 3 they were tested using a number of data sets from measurements made in a range of different locations. The higher one goes in the boundary layer the more uncertain the ideal formulae become. Profiles in the upper part of the boundary layer are important because of their influence on plume rise and dispersion from tall stacks. Turbulence at these heights determines how fast material will return to the ground.

As discussed above, under relatively ideal conditions, the atmospheric boundary layer structure is in principle determined by a few fundamental parameters. However the understanding of turbulence is such that it is not possible to calculate this structure from first principles. This is the reason why the dependence of profiles of wind, temperature and turbulence properties on the fundamental parameters is generally investigated empirically. Working Group 3 investigated such empirical relations and tested their performance. The ability to predict such profiles is crucial in modern approaches to calculating dispersion.

A number of sample data sets, including some laboratory data from water tank experiments, were chosen to test some of the commonly applied formulae describing profiles. Although not a systematic review, the examples indicated some discrepancies. In full-scale atmospheric data many of the formulae did not appear to work well, but it was felt that this could be due to the influence of coastal effects on the measurements. In tank experiments it was shown that the upward and downward motions need to be described by different time scales. This illustrates the limitations of existing theoretical formulae. Although these formulae have been useful for interpreting data sets their usefulness in deriving profiles is shown to be limited and should be used with caution in complex situations such as coastal regions. Working Group 3 was able to make some recommendations regarding profiles in the lower layers of the atmosphere in flat, homogeneous terrain, based on Monin-Obukhov similarity theory which they felt was a good starting point for applications to dispersion models.

2.7 Wind Flow Models over Complex Terrain for Dispersion Calculations (Topic of Working Group 4)

The wind field controls pollutant dispersion though transport and dispersion. In complex terrain the assumption that the wind field is uniform which underlies most regulatory models no longer applies. Working Group 4 distinguish various types of complex terrain such as non-uniform flat terrain, a single hill, a single valley, hilly terrain, complex topography (mountainous), and very complex topography. Appropriate modelling techniques should be applied in each situation. Two broad categories of models are distinguished. Those which are designed to produce a steady wind field and those for which the time-evolution of the atmospheric flow is calculated. Amongst the former, one approach is to use analyses of meteorological data applying mass conservation to interpolate the full flow field. In some cases the full dynamical equations are linearised to derive a flow field with the advantage that little data is required. To calculate the time evolution of the flow field requires a model in which the full dynamical equations are solved, so that these models need substantial computer resources. In some cases, approximations are made to simplify the basic conservation equations in situations where, for example, vertical variations are over much shorter length scales than horizontal variations.

Although a number of models have been identified the problems of applying them in regulatory applications is considerable. These were summarised as being: their complexity, defining appropriate boundary conditions, the impracticality of calculating the time evolution over the long periods required for regulatory purposes as well as the tendency to neglect certain features of the true wind field. Working Group 4 concluded that it is now feasible to use flow models for practical applications. However their use remains a matter for experienced users. To help with the application of flow models in practical situations the Working Group have produced a number of tables showing the situations for which the main types of models are suitable. Guidance is given on matters such as the meteorological and terrain data needs, the computer power, the level of expertise and the range of application. This represents a step towards ensuring that in situations where the usual regulatory models would not normally be appropriate, the best decisions are made regarding alternative methods.

2.8 Dispersion Climatologies

The four Working Groups on the surface energy balance, the mixing height, vertical profiles and wind flow models were concerned mainly with considering the problem of predicting parameters influencing dispersion in a given situation. The problem of representing climatologies for dispersion applications is also a problem of some importance. Examples of the type of question to be considered are:

How many years' data are needed to represent the dispersion climatology reliably?

How far from the site of interest can one measure the climatology without introducing large errors?

Is it possible to use long duration records from a distant site together with short duration on-site measurements to synthesize a long duration climatology for the site of interest?

Is there much difference between using meteorological data sorted into categories with statistics of how often each category occurs and using sequential data?

How should one choose the category boundaries if using statistics of meteorological data divided into categories?

What is the balance between running many meteorological cases with a fast model and fewer cases with a more sophisticated model?

There was insufficient interest among the participants of COST 710 to set up a separate Working Group on these matters. This was partly because the most important of the above issues, the question of whether to use statistical categorized meteorological data or to use sequential data, is becoming less important for three reasons.

Firstly the enormous increases in computing power have made the use of sequential data easier. Secondly the increased complexity of models and the range of problems tackled makes statistical data less convenient. (If one's meteorological input is characterized by a large number of parameters e.g. humidity for condensing plumes, lapse rate above the boundary layer for plumes which penetrate the inversion, precipitation for washout, as well as the basic parameters of wind speed and direction, surface heat flux and boundary layer depth, then one needs a large number categories to represent the climatology accurately. As the number of parameters increases the number of categories required rapidly multiplies, so that eventually a sequential approach may be preferred.) Finally, as discussed in the report of Working Group 4, the spatial variability of meteorology and the temporal variability can be important in many cases, even over relatively short ranges if the terrain is complex, and such effects cannot be included in a statistical approach. However it is still not generally practical to routinely run the most complex dispersion models for, say, 10 years of hourly data and so it is likely that there will still be a role for statistical meteorological data for some years to come.

Some work on climatologies for dispersion applications for a flat site in the UK was presented at the Fourth Workshop on Harmonization within Atmospheric Dispersion Modelling for Regulatory Purposes in Ostend, 1996 (see Appendix A2). The study of Davies and Thomson presented at this conference considered the issues of the number of years of data required, the differences between using sequential data and statistical categories, the differences between different choices of statistical categories, and the differences caused by using meteorological data from meterological sites at various distances from the location of interest. Davies and Thomson found that using only three years' data gave acceptable predictions but that one year was not long enough. The differences arising from the use of sequential and statistical data were small. Perhaps the most interesting result was that predictions for a power station type source were more sensitive to how the data was treated than predictions for a factory source. This implies that the type of source needs to be considered in any future consideration of these issues.

2.9 Preparation of Design Gradient Wind Atlas for Europe

A further climatological problem associated with dispersion is how to obtain representative surface wind conditions in areas of Europe where data is sparse. Within COST 710 Szepesi and Fekete (see Section A2.2 regarding publications) have considered this problem and have produced a Design Gradient Wind Atlas. This contains information, such as the relative frequency of west north west winds for all locations in Europe and the mean wind speed in the west north west direction. The aim is to provide readily available regionally and temporally representative wind flow statistics at any point. The intention is that the surface wind at any site can be obtained from these wind maps using model corrections for terrain, surface roughness and obstacles.

One of the most important aspects of pollutant transport is to obtain the representative flow at the height of the plume. Locally observed winds are often biased. A smoothed flow pattern is more representative of a region and can be used to reveal inconsistencies in siting, measurement or data analysis. To ensure that climatic variations in wind conditions are accounted for, long-term (~ 30 year) records of wind data should be used. If such data is not available then short-term (1-5 year) data series may be considered provided that both the periods have similar Grosswetterlagen frequency distributions. A Design Gradient Wind Atlas should take into account the following principles: (a) it should be based on all long-term (10-30 year) 00.00 and 12.00 UTC wind data for Europe at 850 and 700 hPa pressure surface heights, (b) where only shorter term (1-5 years) data series are available they should be checked against long-term Grosswetterlagen statistics before inclusion, (c) smoothing ensures representative data for mesoscale flow in any region.

A preliminary wind atlas was prepared based on two years (1980-1981) and 850 hPa wind statistics. The period was selected because the radiosonde network in Europe in these years was at its densest. Long-term wind statistics were obtained from the following countries: UK for 12 years between 1976 and 1987 at 00.00 and 12.00 UTC at 850 and 700 hPa, Germany for 30 years between 1961 and 1990 at 00.00 and 12.00 UTC at 850 and 700 hPa, Hungary for 28 years with soundings and pilot balloon statistics at 00.00 and 12.00 UTC at 850 and 700 hPa, Switzerland for 32 years between 1959 and 1990 at 00.00 and 12.00 UTC at 925, 850 and 700 hPa, Poland for 20 years between 1971 and 1990 and Finland for 31 years between 1965 and 1995. Further countries have notified their intention to participate in this exercise.

The comparison of data originating from the preliminary wind atlas and the long-term data showed that gradient wind data over two years approximated long-term patterns if a short period of normal years with characteristic Grosswetterlagen distribution is selected. Short-term wind speeds approximate long-term averages better than wind direction data do. The conventional 16 meteorological sector distribution better meets the needs of dispersion estimates than a 12 sector system. Follow-up work is planned to extend the work to the rest of Europe.

3. Conclusions

Formulae for the fundamental parameters and profiles of turbulence in the boundary layer have been widely and successfully exploited to reduce data to manageable proportions. However the comparisons between the formulae and observations considered by the Working Groups of COST 710 have not been able to produce consistently good agreement for a number of reasons. Accepting the need for better empirical data for use in testing current methods, it is reasonable to conclude that all current methods, regardless of further testing, are likely to be associated with errors in certain non-ideal situations. Further improvements may come from the widespread introduction of remote sensing technology to improve measurements. Although remote sensing methods depend on the correct interpretation of surrogate information they have the advantage of providing much more information in space and time than routinely used meteorological instrumentation. The other line of approach is to exploit the use of improved numerical models and high speed computing. This has the obvious application to meteorological processing in complex terrain which was not studied sufficiently in COST 710 and needs to be developed further. Situations involving precipitation were not considered although precipitation processes can strongly influence pollution concentrations.

A long-term network of well-equipped sites monitoring the atmospheric boundary layer in different climatic regions should be funded since a comprehensive long-term data base is urgently needed. It would also be highly desirable to strengthen routine measurements of the parameters needed for mixing height determination by introducing additional remote sensing technology. In the mean time in practical applications of air quality dispersion models the limitations on the accuracy of predictions arising from limitations in the description of meteorological data should be recognised in decision making. The models based on the use of fundamental parameters of the atmospheric boundary layer do have a useful degree of skill and are to be recommended. Dispersion models are likely to obtain the appropriate distributions of concentrations arising from the variations in meteorological conditions, but are unlikely to predict the right concentration on particular occasions.

COST 710 did not include any studies into the sensitivity of dispersion calculations to errors in the parameters studied. This will of course vary with the dispersion model but it would be useful if further work is conducted to assess the significance of errors and identify where further effort in reducing errors would be most effectively directed.

Appendices

A1 General Description of COST Action 710

A1.1 Introduction *taken from Annex II of the Memorandum of Understanding*

There are a number of initiatives within Europe to increase cooperation between organizations developing improved methods for predicting atmospheric dispersion: particularly active in this area has been ERCOFTAC (European Research Community for Flow, Turbulence and combustion), co-sponsor of important workshops on this topic in Denmark (1992), Switzerland (1993) and Belgium in 1994. Ideally, the results from these new models should lead to consistent environmental assessments when they are applied. This requires not only appropriate formulations, but also (the point which this COST Action will address) more uniformity in the provision of standardized meteorological data used as input to the models. In these circumstances it is appropriate for the providers of the required data, which include in particular the National Meteorological Services, to attempt to coordinate the methods they use, or will use, to preprocess the data.

Fortunately there is already global uniformity in meteorological observing practices and in the range of meteorological variables observed at standard synoptic meteorological stations, and radiosonde stations. It is largely a coincidence that these observations provide in principle all the data needed to run existing and "new-generation" dispersion models, since observing practices have been shaped principally by the requirements of aviation rather than air pollution. However, except for simple models using Pasquill's method to account for the influence of atmospheric stability on dispersion, the standard data need significant processing to provide the fundamental parameters which will eventually represent meteorological influences in all methods of dispersion prediction. There are numerous different methods and schemes for deriving the required meteorological data. Just as in the case of the dispersion models themselves, it is not appropriate at present (nor indeed probably in the future) to attempt to limit the number of methods used, or in the extreme to prescribe one single set of procedures. The need is to understand just how well each method performs when compared with reliable, observation-based, derivations of the fundamental parameters.

It is especially appropriate to address these issues within a COST Action. There should be interest either in participation or in the results from most if not all European countries because of the need for sound procedures in all aspects of regulation of polluting emissions into the atmosphere.

A1.2 Objectives of Action *taken from Annex II of the Memorandum of Understanding*

The original Pasquill-based dispersion prediction schemes are now being superseded by more fundamentally based methods of predicting atmospheric dispersion: in due course the new-generation models will be those used throughout Europe.

These models characterize the dispersion properties of the atmosphere in terms of fundamental parameters from which, in principle, dispersion may be uniquely described. The objectives of the action are then to:

(i) encourage uniformity in the way in which the dispersive properties of the atmosphere are characterized by meteorologically-based fundamental parameters;

(ii) intercompare the methods used in different countries to derive these fundamental parameters by testing them against reliable, observation-based derivations of the fundamental parameters;

(iii) identify the observational data sets in (ii), and exchange them in an agreed format.

A1.3 Scientific Content of Action *taken from Annex II of the Memorandum of Understanding*

(i) Characterization of the dispersive properties of the atmosphere by meteorologically based fundamental parameters

Dispersion may be described by a number of different fundamental parameters, some of which are not independent. Different dispersion models may require different combinations of these parameters. The Action will therefore:

(a) review the fundamental parameters, and assess the merits of different combinations of them, taking into account especially that they may be required over terrain with different characteristics from those where the meteorological data used to derive them are obtained.

For applications such as regulation or impact assessment the dispersion models may be run with summaries (frequency distributions) of the meteorological-based inputs rather than time series. The most appropriate ranges of parameter values in each of the "bins" in these input matrices are likely to vary significantly across Europe because of the major differences in climate in both North-South and East-West directions across this region. The Action will:

(b) review the model input matrices and recommend optimal ranges of values for each parameter "bin", for different climatic regions of Europe.

(ii) Intercomparison of methods used to estimate the fundamental input parameters

The project will:

(a) identify the current methods used to derive from standard meteorological data the fundamental parameters of dispersion;

(b) test the results from these methods against parameter values estimated from reliable boundary-layer experiments and from radiosonde data;

(c) make recommendations on the methods.

(iii) Data-sets used in the comparison of methods of estimating the fundamental input parameters

The Action will:

(a) identify data sets suitable for the studies under (ii)b;

(b) arrange for these data to be put in an agreed format and sent to those involved in (ii)b.

A2 Fourth Workshop on Harmonization within Atmospheric Dispersion Modelling for Regulatory Purposes

One expectation when the Action commenced was that a Workshop should be held to present results to a wider audience. This took place as part of the Fourth Workshop on Harmonization within Atmospheric Dispersion Modelling for Regulatory Purposes, in which a special session was devoted to the harmonization in the preprocessing of meterological data for dispersion models. This Workshop was held on the 6-9 May 1996 in Ostend, Belgium, and was attended by 180 participants from 30 different countries. The local organiser was VITO, the Flemish Institute for Technological Research, Mol, Belgium. The final proceedings of the Workshop will appear in a special issue of *The International Journal of Environment and Pollution* (IJEP)*, Vol 8, Nos 3-4, 1997* .

A2.1 COST 710 Papers Appearing in the International Journal of Environment and Pollution

Meteorological data for dispersion modelling: a brief report on the COST 710 programme on pre-processing and harmonization
G Cosemans, J Erbrink, B E A Fisher, J G Kretzschmar and D J Thomson

COST 710 - Working Group 1: Status report and preliminary results
U Pechinger, E Dittmann, P Johansson, G Omstedt, A Karppinen, L Musson-Genon and P Tercier

Surface energy balance: analysis of the parametrization of the ground heat flux
P Tercier, R Stübi , A Chassot and P Mühlemann,

Direct and indirect methods for momentum and turbulent heat flux computation in the surface layer
R Sozzi and M Favaron

Results of sensitivity analysis and validation trials of some methods to evaluate scaling parameters
M G Longoni, G Lanzani and M Tamponi

On the determination of mixing height: A critical review

F Beyrich, S-E Gryning, S Joffre, A Rasmussen, P Seibert, P Tercier and G Verver

Boundary layer depth: Sensitivity study
R Stübi, A Chassot and P Tercier

A model for the height of the internal boundary layer over an area with an irregular coastline
E Batchvarova and S-E Gryning

Improvements of the prediction of Gaussian models by using dispersion parameters calculated from atmospheric turbulence measurements. Applications to strong pollution episodes near an industrial zone
A Coppalle, P Parantheon, L Rosset, V Delmas and M Hamida

Vertical profiles
J J Erbrink, P Seibert, G Cosemans, A Lasserre-Bigorry, H Weber and R Stübi

Study of turbulent atmospheric dispersion under strong stability conditions
P Boyer, O Masson, B Carissimo, F Ansemet and M Coantic

A 2-D meteorological pre-processor for real-time 3-D ATD models
G Brusasca, S Finardi, M G Morselli and G Tinarelli

A 3-D wind and temperature pre-processor for ATD models
G Calori, S Finardi, C Mazzola and M G Morselli

Realistic approach to 2-D flow modelling for complex terrain
H Erdun, S Incecik, M O Kaya and I Ozkol

Mesoscale modelling of atmospheric processes over the west-central Mediterranean area during summer: Meteorological modelling
R Salvador, E Mantilla. J M Baldasano and M Millan

Meteo-geographical data input tools used with ATD "DEMOKRITOS" code
P Deligiannis, N Catsaros, M Varvayanni and J G Bartzis

Statistical analysis of prognostic mesoscale flow model results in the framework of APSIS
R Kunz and N Moussiopoulos

Meteorological pre-processing for dispersion models in an urban environment
M W Rotach

Boundary layer parametrization for Finnish regulatory dispersion models
A Karppinen, S Joffre and P Vaajama

Verification of the meteorological pre-processor MEPDIM
T Bohler

Comparison between different pre-processors during high latitude winter conditions
P E Johansson

Dispersion modelling in complex terrain using wind climatologies
M Wichmann-Fiebig and W Brücher

A meteorological data base system for practical dispersion modelling: First results of model test applications
B Scherer and E Reimer

Investigating the importance of pre-processing in estimation dispersion climatology
B M Davies and D J Thomson

A2.2 A Selection of COST 710 Papers Appearing in the Scientific Literature

Berger H, Ruffieux D, Stübi R, 1996, Time evolution of the planetary boundary layer estimated by merging SODAR, wind profiler and soundings data, Proceedings of the 18th International Symposium on Acoustic Remote Sensing and Associated Techniques of the Atmosphere and oceans, Moscow 27-31 May 1996

Beyrich F, Gryning S-E, Joffre S, Rasmussen A, Seibert P and Tercier P, 1997, Mixing height determination for dispersion modelling - A test of meteorological preprocessors, 22nd NATO/CCMS International Technical Meeting on Air Pollution Modelling and its Application, Clemont-Ferrand France, 2-6 June 1997 8pp

Erbes G and Pechinger U, 1998, Comparison of synoptic-based preprocessor estimates with measured boundary layer parameters, submitted to: NOPEX special issue "Agricultural and Forest Meteorology (AGMET)".

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