METEOROLOGY APPLIED TO URBAN AIR POLLUTION PROBLEMS COST 715

Bernard Fisher*
University of Greenwich, School of Earth and Environmental Science, Medway Campus, Chatham, Kent ME4 4TB, U K

Jaakko Kukkonen
Finnish Meteorological Institute, Air Quality Research, Sahaajankatu 20 FIN-00810 Helsinki, Finland

Michael Schatzmann
University of Hamburg, Meteorologisches Institut, Bundestrasse 55
D-20146 Hamburg, Germany

Abstract: The requirements of the framework Directive on air quality assessment and management introduce real practical problems for the meteorological community. Some of the meteorological variables needed in urban air pollution assessments are not routinely measured and in normal circumstances the number of meteorological stations in urban areas is limited to a few sites often just at airports. The European wide project COST 715 on "Meteorology applied to Urban Air Pollution Problems" has been set up to review these problems. This paper describes limitations of current methods. It recognises that the urban boundary layer is a non-equilibrium situation where standard theories applied to rural areas may not be valid. It shows that predictions of concentrations for assessments should always state the uncertainty associated with them. This uncertainty can be large because of the complexity of urban pollution situations, particularly the description of the local urban meteorology. An example is given of how with some additional, local meteorological measurements, the uncertainty can be reduced. The paper concludes by listing some of the key areas where further work is required. Information about the COST 715 project is available from the Web site at http://www.dmu.dk/atmosphericenvironment/cost715.htm.

Keywords: Meteorology, surface heat flux, roughness length, urban, air pollution, street canyon, dispersion, uncertainty, ensemble average, Bayes theorem

Reference

*Present address National Centre for Risk Assessment and Options Appraisal, Environment Agency, Steel House, 11 Tothill Street, London SW1H 9NF, U K

1 Introduction

One of the key aims of European environmental policy is to improve air quality in European cities and urban areas. The framework Directive on air quality assessment and management was adopted by the Council of Ministers of the European Union in September 1996. It will lead to daughter Directives on up to 13 air pollutants, for which assessments of air quality in certain areas (mainly large urban areas with high populations) will be required. The first European 'daughter' directive, setting objectives and limit values for sulphur dioxide, NO_2, particulates and lead was adopted in the middle of 1999. Remedial plans may need to be drawn up in areas of poor air quality. To undertake these tasks, reliable air pollution models are necessary to supplement, and sometimes replace, measurements and also to investigate future emission scenarios. These models will need accurate meteorological input variables consistently applied within EU member states.

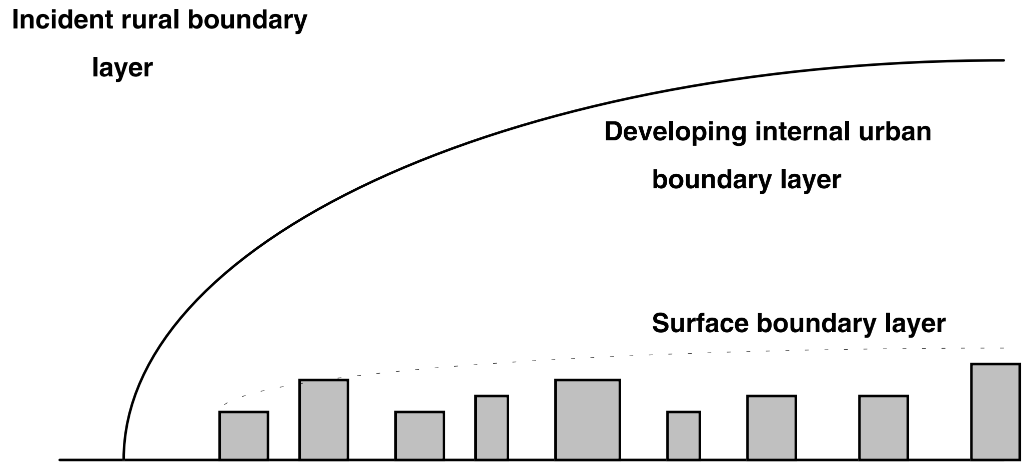
These requirements introduce real practical problems for the meteorological community. For example some of the meteorological variables are quantities that are not routinely measured, such as the mixing layer depth. In normal circumstances the number of meteorological stations in urban areas is limited to a few sites, often just at airports.

The action COST 715 continues the work of two previous actions, COST 710 and COST 615. Action COST 710 on the harmonisation of the pre-processing of meteorological data for atmospheric dispersion models started to address these issues and made good progress. It identified schemes in current use for obtaining the key meteorological variables associated with air pollution (Fisher, Erbrink, Finardi, Jeannet, Joffre, Morselli, Pechinger, Seibert and Thomson, 1998). The action COST 615 has produced an inventory of models of urban air pollution, ranging from Gaussian models using standard dispersion categories to numerical flow models (http://www.belspo.be/cost).

2 Essential differences between urban and rural dispersion climatologies

The urban situation presents special problems to the air pollution modeller. In many situations the starting point for urban dispersion is a simple dispersion scheme applicable to rural areas suitably modified. The presence of the urban area introduces two complicating features to the rural boundary layer built up in the approach flow to the urban area, illustrated in Fig 1. The roughness elements of the urban area are typically much larger than the rural roughness elements and the urban area is associated with surface heating. These effects introduce a developing boundary layer over the urban area, which modifies the incident profile. In addition one can visualise a modified surface layer above the roughness elements. In ideal convective and stable atmospheric boundary layers the wind profile near the surface should follow a logarithmic profile characteristic of neutral conditions. Rotach(1995) has shown that the wind profile does not follow a logarithmic profile in the surface layer, which is divided into an inertial sub-layer and a roughness sub-layer near the surface. The structure of wind and turbulence between roughness elements i.e. within street canyons assumes importance. It is also of interest to note that the wind profile is not logarithmic and the turbulence profile is non-uniform in courtyards with various aspect ratios, studied in a wind tunnel by Hall, Walker and Spanton(1999).

Oke(1987) has shown that the extra urban heating introduces significant modification of the dispersion conditions. The urban heat island effect is up to $100W/m^2$ during the daytime and $10W/m^2$ at night, so that dispersion categories can be modified. Moreover the internal boundary changes the extent to which pollution may spread. The presence of the urban area introduces a spatial modification to the rural boundary layer used as the basis for normal dispersion calculations. The internal urban boundary layer will differ in daytime and night conditions. Figure 1 shows that the two zones of greatest difficulty are at the top and the bottom of the urban boundary layer. This paper discusses these issues within the context of assessments of urban air pollution bearing in mind the objectives and limits set in European daughter directives. The COST 715 action will recommend the best way of obtaining appropriate meteorological data and using meteorological information in urban air pollution assessments.



Not drawn to scale

Figure 1 Schematic representation of urban boundary layer development

3 Ensemble average concentrations

Any atmospheric dispersion model will have a degree of error due to unavoidable inaccuracies in the recorded meteorological data and the simplifications made in the model algorithms for atmospheric processes. In addition atmospheric mixing has an inherent degree of randomness due to the turbulence. As a result even if a plume is released on a series of occasions under fixed and identical meteorological conditions, the actual behaviour of the plume will still be different every time. Even though the value of every parameter affecting dispersion is identical, the path and dispersion of the plume will be different due to turbulence in the mixing processes. If a release event is repeated many times then it is possible to determine the average plume behaviour, with a statistical distribution around this average. This is the approach taken by computer models of dispersion, which are based on statistical descriptions of atmospheric fluid mechanics. Although turbulence randomises the path of a plume at any given moment, it is possible to determine the probability distribution of plume behaviour, and to prediction the pattern of dispersion when averaged over many sample periods. Models can give quite reasonable predictions of the actual behaviour when averaged out over many runs, however model results for short time intervals will rarely match the actual dispersion due to the inherent random error from turbulence. Because of this inherent random error, it is essential to use large data sets of results to generate “ensemble mean” results. If the modelling errors are truly random (i.e. under-prediction is as likely as over-prediction) and the data set is very large, then the modelled average should be unaffected. If the model is a reasonable approximation to the actual atmospheric processes of dispersion, then the modelled long-term average concentrations can be expected to be reasonably close to the actual long-term average concentrations.

In principle other ensemble model values, such as the 99.9th percentile concentrations of the entire data set, should also be reasonably close to the actual values if the data set is sufficiently large to smooth out the effect of the random errors. These extreme values will always be based on only a few model results (e.g. the modelled worst 8 hours of the year for the 99.9th percentile). There is therefore a greater potential for one or two anomalous hours to significantly affect the model results for these values compared to the annual mean result which is based on nearly 9,000 modelled hours. As a result of this data set limitation in modelling the few hours of extreme concentrations, the model results for the upper percentile concentrations (and especially the worst hour) are less reliable than the annual mean.

These features do not undermine the validity of the results from air dispersion modelling, but they do emphasise the need for caution in drawing conclusions from modelling alone. This is particularly true when modelled values for maximum concentrations are being evaluated. Applied dispersion models should be validated against standard data sets of recorded concentrations and meteorological conditions. These validation exercises can be used to confirm that the models give reasonably accurate predictions of average concentrations over the longer term, including the upper percentile concentrations. However there will always be differences between models and the measured concentrations. These differences become far more marked at the extremes. As the concentration calculated by a model is an ensemble average, associated with the concentration should be a probability distribution describing the frequency of occurrence of concentrations greater or less than the ensemble mean. This is often conveniently forgotten.

4. Concentrations in urban street canyons

The exposure of the population to air pollution in urban areas is made up of three components: (1) the urban background (pollution that diffuses into the street from above and whose concentration, apart from emissions, is largely determined by dilution within the developing internal boundary layer), (2) the direct impact of road transport emissions on persons within the same street, and (3) the re-circulation of air within a street canyon. In light winds or when the wind is parallel to the street axis a re-circulating flow will not be set up and the dispersion at the surface may be considered like a box with a open lid. The re-circulating and direct components may then be considered equivalent.

In order to describe pollution in street canyons, models of the direct and re-circulating components have been proposed. The direct component on the windward side of the street when the street is aligned perpendicular to the wind direction and there is no re-circulation, is typically (Berkowicz, Hertel, Larsen, Sørensen and Nielsen, 1997):

$$C_{diir} = \sqrt{\frac{2}{\pi}} \frac{Q}{W\sigma_w} \ln \frac{h_0 + (\sigma_w / u_b)W}{h_0} \tag{1}$$

where Q is the emission strength per unit length of street, W is width of street, σ_w is the vertical turbulent velocity fluctuation including traffic generated turbulence near the ground in the street, h_0 is the initial dispersion in the wake of vehicles typically 2m, and u_b is the wind speed at the street level.

The magnitude of the re-circulating component of the concentration on the windward side of the street when the vortex extends through the whole street canyon is of order (Berkowicz, Hertel, Larsen, Sørensen and Nielsen, 1997):

$$C_{rec} = \frac{Q}{W\sigma_{wt}} \tag{2}$$

where σ_{wt} is the rms vertical turbulent velocity fluctuation at roof level.

These are elegantly simple but how does one obtain the wind speed, wind direction and turbulence levels in the street? It would be valuable to have measurements of these parameters in the street and at roof level. It is not clear how to relate these to wind profiles made elsewhere in the urban area at presumably greater heights, or to relate them to the wind profile in the incident boundary layer air flow. This is the sort of information required for routine urban dispersion calculations. The dependence of turbulence on thermal stratification is taken to be small at street level, though it may be more significant at roof level. It may be argued that high pollution situations are associated with a high density of motor traffic and hence considerable vehicle generated turbulence.

The ratio between the direct and re-circulating components is seen to be

$$\sqrt{\frac{2}{\pi}} \frac{\sigma_{wt}}{\sigma_w} \ln\left(1 + \frac{\sigma_w W}{u_b h_0}\right) \tag{3}$$

and thus depends on turbulence levels at street and roof level for which there are no practical, generally applied algorithms. Street canyon models specify the zone in the street which is subject to recirculation, and the zone which is directly affected by vehicle emissions. For streets of height approximately equal to width, it is generally assumed that the re-circulating zone includes the whole street unless the wind is light or its direction is nearly parallel to the street axis. However the assumption of a steady situation may not be justified. Instead there may be periods when the windward side of the street is exposed alternately to the recirculating or direct component. Similarly the leeward side of the street may be alternately exposed to no direct component or to the recirculating component. The long-term mean of the concentration on the windward side of the street C_{street} is

$$C_{street} = p(C_{dir})C_{dir} + p(C_{rec})C_{rec} \tag{4}$$

where $p(C_{dir})$ is the probability the receptor is exposed to the direct component and $p(C_{rec})=1-p(C_{dir})$ is the probability the receptor is exposed to the re-circulating component. The short-term average concentration in the street also equals C_{dir} with a probability $p(C_{dir})$ and equals C_{rec} with a probability $p(C_{rec})$.

When measurements of wind direction above and below roof level are available it should be possible from the wind shear to determine whether or not a vortex is present. By applying Bayes theorem a much improved estimate of the concentration in the street can be made. It is assumed that p(low shear|C_{dir}) the probability, given no recirculation, that the street level wind is roughly parallel with the roof level wind, and p(low shear|C_{rec}) the probability, given recirculation, that the street level wind is roughly parallel to the roof level wind, are known. The probability that the concentration on the windward side of the street is equal to the direct component C_{dir}, given that the roof and street level winds are roughly parallel, is p(C_{dir}|low shear), given by

$$p(C_{dir} \mid lowshear) = \frac{p(lowshear \mid C_{dir})p(C_{dir})}{p(lowshear \mid C_{dir})p(C_{dir}) + p(lowshear \mid C_{rec})p(C_{rec})} \qquad (5)$$

p(C_{dir}) and p(C_{rec}) are the prior probabilities of whether or not recirculation will occur. As an example it is assumed that the direct component occurs less often; say p(C_{dir}) equals 0.3 and p(C_{rec}) equals 0.7. If the difference between the roof and street level wind is a good predictor of the presence of recirculation, so that the conditional probabilities p(low shear|C_{dir}) and p(low shear|C_{rec}) are 0.9 and 0.1 respectively, then from information about the roof and street level wind directions, a better estimate of when the concentration equals C_{dir} can be made

$$p(C_{dir} \mid lowshear) = \frac{0.9 \times 0.3}{0.9 \times 0.3 + 0.1 \times 0.7} \approx 0.8 \qquad (6)$$

An improvement in the estimate of when to apply the recirculating formula C_{rec} can also be found by applying similar formulae.

The direct component C_{dir} could also be calculated using the CALINE4 model (Benson, 1992) and written in a form, which shows that it is a function of a number of input parameters:

$$C_{dir} = fn(N, E, W_{mix}, \sigma_z, \theta, u, S, h, z_0, H, \sigma_\theta, t_L) \qquad (7)$$

where N = traffic flow, E = emission factor for average vehicle, W_{mix} = mixing zone width (or h_0 = initial vertical mixing), σ_z = vertical dispersion coefficient, θ = wind direction, u = wind speed, S = stability, h = mixing height, or internal urban boundary layer depth, z_0 = roughness length, H = roadway height, σ_θ = horizontal standard deviation of wind direction, t_L = Lagrangian time scale, showing that the concentration is dependent on at least 12 parameters, nine of which are dependent on urban meteorology. Admittedly the results may not be strongly dependent on some parameters such as h, the depth of the internal boundary layer or z_0, the local roughness length. Near the street, dispersion is more dependent on the mixing zone width, and stability is less important. The concentration is not always directly proportional to the total vehicle source strength Q (=NE) because of possible variations in the geometry of traffic lanes.

To test results of a model fully, one would have to make measurements under a wide range of conditions. To test all the dependencies between the parameters one would need at least 5^{12} (≈240 million) measurements since each parameter has a range of values which typically could be represented by 5 values. In order to test the model fully a sensitivity analysis would need up to 3^{12}≈500,000 runs of the model, assuming high, medium and low values for each parameter, unless similarity theory, based on dimensional analysis, would allow one to transform the functional relationship into a dependence on a reduced number of dimensionless parameters. The Bayesian approach in which measured data is used in combination with a model to improve predictions of a model, reduces the amount of validation compared to a purely theoretical approach.

5. Internal urban boundary layer depth

The internal boundary layer is not of constant height though it is commonly assumed to be in dispersion calculations. It should tend to a certain limit with increasing fetch over the urban area. Its spatial dependence may not be important if the mixed layer is very deep. Crucial for episodes is the situation when the layer is shallow. One is then concerned with the lowest values, which are expected to occur at night. Lena and Desiato(1999) have recommended a practical method for estimating the nocturnal boundary layer height in urban areas.

The question arises as to what are the most extreme stability conditions within an urban area and what is the minimum positive value of the Monin-Obukhov length L (m), when the surface sensible heat flux H_0 (W/m^2) is large and negative, such as during cooling on a clear night. L is inversely proportional to the surface sensible heat flux, according to $L=-10^5 u_*^3/ H_0$, where u_* is the friction velocity (m/s) and the constant of proportionality has dimensions, but is approximately constant. The greater the cooling, the smaller is the value of L, with a minimum value in urban areas of about 40m. The minimum value of L is expected to be higher in urban areas than in surrounding rural areas because of the greater man-made and storage contributions to the heat flux and the lower water vapour flux. L is the height in the atmosphere up to which wind shear effects dominate. Low values of L imply extreme wind shear in the lowest layers generating greater mechanical turbulence and higher values of u_*.

Middleton(1998) corrects the rural nocturnal cooling flux by two components: a decaying stored solar energy and an additional man-made heat flux in the urban area, in order to estimate the surface cooling in an urban area. The amount of sensible heat is assumed to be a greater faction of the solar input accumulated during the daytime in urban areas compared with rural areas. During the night cooling takes place and the stored sensible heat is lost to the atmosphere. The magnitude of the man-made contribution is taken to be 3 W/m^2 in suburban areas and 6 W/m^2 in the city centre. In the ADMS model (Carruthers, Edmunds, Lester, McHugh and Singles, 1998) a minimum vales of L of 100m is adopted in London with lower values cited for other urban areas, where presumably the urban heating effect is smaller.

Another problem arises with the definition of meteorological categories. The standard Meteorological Office data gives the upper boundaries of the lowest surface heat flux as -30 W/m^2. The upper limit of the lowest 10 metre wind speed category is set at 1.5m/s and below this calm conditions are assumed. For high pollution incidents associated with low wind speeds and a large cooling rate it is not clear how values of wind speed and heat flux should be chosen.

Practical dispersion calculations depend on schemes for pre-processing meteorological data, which are available routinely from meteorological observing stations. These are discussed in the report of COST 710. The meteorological input may typically consist of wind speed, direction, near surface temperature, cloud cover, surface albedo, time of year and time of day. The outputs may consist of surface sensible heat flux, mixing layer height, Monin-Obukhov length and temperature jump across the boundary layer top. The COST 710 report cites exercises in which the algorithms have been tested in situations when detailed boundary layer measurements are available. In tests of daytime and night-time algorithms for predicting surface sensible heat flux using measurements from a rural site in a flat, agricultural site with a roughness length of 0.01m (Galinski and Thomson, 1995), night-time heat fluxes lay mainly in the range 0 to -50W/m^2. Similar studies are necessary for urban sites and one of the aims of COST 715 is to encourage such activity.

6. COST 715 Work plan and Working Groups

This brief review justifies the focus of COST 715. The programme involves 18 countries at the present time. Information about the COST 715 project is available from the Web site at http://www.dmu.dk/atmosphericenvironment/cost715.htm. The programme of COST 715 is divided into the following four working groups.

Working Group 1 Wind field in urban areas

Working Group 1 reviews wind fields in urban areas, and the use and validity of various parametrisation schemes. This Working Group considers the effects of the large roughness elements in urban areas. The Group has reported on wind input data for urban dispersion modelling at the COST 715 Workshop on the Preparation of Meteorological Input Data for Urban Site Studies (Schatzmann, Brechler and Fisher, 2000, in preparation).

Taking into account the diversity of ongoing activities in Europe and elsewhere, it is also relevant to identify pre-processors and models available outside COST 715. The work of other key scientists has been integrated into COST 715. COST 715 co-operates closely with the SATURN project of the EUROTRAC-2 programme. For instance, air quality episodes are also included within the work of SATURN (Working Group MOD4). This is done in co-operation with the EU Training and Mobility Network TRAPOS.

Working Group 2 Mixing heights and surface energy budgets

Working Group 2 considers mixing depth, its determination and diurnal variation, and the use and validity of various parametrisation schemes. This work includes the following tasks:

1. to review the various pre-processors, schemes and models for the determination of the mixing height and the surface energy budget or stability. The case of strong stability and/or light wind conditions are of special interest,
2. to identify and review suitable data sets within and outside the Group which could be used to test and validate the pre-processors and models,

3. to carry out inter-comparisons of different schemes against each other and against data under specific conditions,
4. to assess the influence on the model outputs of certain specific effects, such as complex topography, strong heterogeneity, slopes on radiative fluxes,
5. to assess the suitability of remote sensing tools to estimate canopy characteristics and surface fluxes,
6. to provide recommendations for the improvement of existing pre-processors and models and for the development of new schemes.

Working Group 2 has made recommendations on determining heat fluxes and hence the urban stability, following an expert meeting with N American scientists on "surface energy budgets and mixing depth" (Piringer, 2000, to be published).

Working Group 3: Meteorology during peak pollution episodes

Working Group 3 addresses meteorological conditions leading to air pollution episodes, analyses past episodes and develops and tests air quality forecasting methods. During episodes pollutant concentrations are highest, and the performance of dispersion models is commonly worst.

Problems are different for cities in different European regions (Railo, 1997). In northern European cities, ground-based inversions, stable atmospheric stratification, low wind speed and topography are key factors. Particles and NO_2 are the most important pollutants. Episodes occur typically in winter (NO_2) or spring (particles). In northern and central Europe, re-suspension of particles from street surfaces is an important source of coarse particles.

In southern and central European cities, stable atmospheric stratification, low wind speeds, meso-scale circulation, topography and solar radiation are important factors. Photochemical pollution episodes including O_3, particles etc, occur commonly in summer. Work within the Working Group has to allow for these specific conditions in various European regions.

Over Europe, low wind speeds and stable atmospheric stratification tend to cause episodes. Particulate pollution seems to be important in episodic conditions over the whole European continent. Evaluation of regional air quality is needed in many cases in order to analyse urban episodes, but the work is focused on episodes in urban areas.

The objectives of Working Group 3 include the following:

1. Modelling of episodes, including the review of available models, testing and validation of these and analysis of the main factors causing uncertainties in model predictions (emissions, meteorology and chemistry).
2. Evaluation of practical matters related to episodes, including analysis of the evolution of past episodes in the light of measured and predicted data, evaluation of exceedences of guidelines and limit values, and the influence of measures in order to control episodes. Consideration of the forecasting of episodes will be included. The forecast methods may be based on solving the fundamental conservation equations or on statistical methods.
3. Review of available measured and processed meteorological and concentration data.

Working Group 3 has compiled a Status Report (Kukkonen, 2000), which contains country reports from all participants within this Working Group. Each of these reports includes the main objectives, available meteorological and concentration data, available models, the expected benefits, the funding situation and other related projects. There is a strong emphasis on improvement and evaluation of the simulation of urban meteorology in numerical weather prediction models.

Working Group 4: Input data for urban air pollution models

Working Group 4 addresses the practical issue of how meteorological data is used in dispersion models involving urban areas at the present time. After all models are currently being used for urban air quality assessments in all countries of Europe. Decisions are made routinely as to how conventional approaches should be adjusted to urban conditions. A COST 715 Workshop was held on the Preparation of Meteorological Data for Urban Site Studies (Schatzmann, Brechler and Fisher, 2000, in preparation) to review routinely applied approaches to specifying urban meteorology for application to dispersion modelling. The Workshop report informs the community on the potential and limitations of the approaches followed in different European countries. Moreover information is given on how the present situation could be improved. Various downscaling methods for obtaining wind data on the scale of a city from low resolution wind fields were discussed at the Workshop. Urban dispersion models contain assumptions and simplifications, which need to be justified and proven to be in accordance with reality. Consequently Working Group 4 is concerned with the quality assurance of urban air pollution models in general.

Table 1. The participants of the COST 715 Working Groups include the following with colleagues providing support when appropriate. The chairperson is Bernard Fisher, and the WG chairpersons are Mathias Rotach (WG1), Martin Piringer (WG 2), Jaakko Kukkonen (WG 3) and Michael Schatzmann (WG 4).

Group 1	Group 2	Group 3	Group 4
M Rotach, CH	K. de Ridder, B	R. Salvador, E	R. Almbauer, A
Z. Janour, CZ	A. Baklanov, DK	L. Bozo, H	A. Graff, D
R. Berkowicz, DK	S. Joffre, FIN	J. Kukkonen, FIN	M. Schatzmann, D
V. Prior, P	M. Tombrou, GR	R. Carvalho, P	J Brechler, CZ
D Middleton, UK	M. Piringer, A	G. Schayes, B	
C Sacre, F	A Karppinen, FIN	A. Rasmussen, DK	
M Schatzmann, D	P Mestayer, F	F Bompay, F	
P Kastner-Klein CH	J Ferreira, P	A Coppalle, F	
E Batchvarova BG	D Middleton, UK	B Fay, D	
Z Dunkel Secretary	R Vogt, CH	L Volta, I	
		S Finardi, I	
		E Berge, N	
		L Harvard, N	
		R Sokhi, UK	
		A Visau, Macao	

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