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Urban air pollution modelling and measurements of boundary layer height

F. Davies[a,*], D.R. Middleton[b], K.E. Bozier[a]

[a]School of Environment and Life Sciences, Peel Building, University of Salford, Salford M5 4WT, UK
[b]Met Office, FitzRoy Road, Exeter, Devon EX1 3PB, UK

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Abstract

An urban field trial has been undertaken with the aim of assessing the performance of the boundary layer height (BLH) determination of two models: the Met Office Unified Model (UM) and a Gaussian-type plume model, ADMS. Pulsed Doppler lidar data were used to measure mixing layer height and cloud base heights for a variety of meteorological conditions over a 3 week period in July 2003. In this work, the daily growth and decay of the BLH from the lidar data and model simulations for 5 days are compared. The results show that although the UM can do a good job of reproducing the boundary layer growth, there are occasions where the BLH is overestimated by 30–100%. Within dispersion models it is the BLH that effectively limits the height to which pollution disperses, so these results have very important implications for pollution dispersion modelling. The results show that correct development of the boundary layer in the UM is critically dependant on morning cloud cover. The ADMS model is used routinely by local authorities in the UK for local air-quality forecasting. The ADMS model was run under three settings; an 'urban' roughness, a 'rural' roughness and a 'transition' roughness. In all cases, the 'urban' setting over estimated the BLH and is clearly a poor predictor of urban BLH. The 'transition' setting, which distinguishes between the meteorological data input site and the dispersion modelling site, gave the best results under the well mixed conditions of the trial.

Keywords: Air-quality forecasting; Dispersion models; Doppler lidar; Mixing height; Urban boundary layer

1. Introduction

Remote sensing instruments are very useful for the investigation of the behaviour of the atmospheric boundary layer. This is especially true of those areas of the boundary layer that are difficult or impossible to measure with more conventional instruments, such as the urban boundary layer. A recent report, COST 715, by Piringer and Joffre (2005), has summarised urban field campaigns in Europe. They comment that horizontal non-homogeneity of the boundary layer height (BLH) is a major effect of urban surfaces and, therefore, the incorporation of urban-type surface forcing is important for the correct modelling of urban pollution dispersion. The dispersion of pollutants

*Corresponding author. Tel.: +44 161 295 4449;
fax: +44 161 295 5015.
E-mail addresses: F.Davies@salford.ac.uk (F. Davies), Doug.middleton@metoffice.gov.uk (D.R. Middleton), K.Bozier@salford.ac.uk (K.E. Bozier).

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is dependent on many meteorological parameters (Collier et al., 2005), and the mixing height or boundary layer depth is one of the parameters that defines the volume of air through which the pollution is mixed. The work in this paper shows results from a pulsed Doppler lidar trial, where measurements of BLH have been made over West London in the UK.

In the UK, the Environment Act (1995) requires local authorities to conduct a review of 'the likely future air quality within the relevant period' over which improvements are sought. National air quality forecasts use the Met Office's dispersion model, NAME (NWP Gazette, 2000), which uses input data from the Met Office Unified Model (UM) and local air-quality assessment is done by local government using the atmospheric dispersion model, ADMS (Holtslag and van Ulden, 1983; CERC, 2001). In 2002, the UK Treasury funded a 3 year research project in the UK, under the "Invest to Save Budget", which was managed by the Department of Environment Food and Rural Affairs (DEFRA). The overall aim of the "Invest-to-Save Budget" Project 52 (ISB52), was to obtain new field data to improve the dispersion models performance of air-quality forecasting (see ISB52, 2004). The ISB52 project team comprised of QinetiQ, UK Met Office, University of Salford and University of Essex. In this paper, we compare the BLH determination from the current UK pollution dispersion models against measurements from pulsed Doppler lidar over a variety of meteorological conditions. The aim of the paper is to examine the model behaviour compared to the lidar results and highlight the differences to provide insight to the model limitations and errors. Important considerations associated with urban air pollution dispersion modelling are discussed.

During this project, a field campaign was carried out over a 3 weeks period during July 2003, at the Royal Air Force base at Northolt, situated on the western border of London in the UK. In this paper, we show the daily BLH development over 5 separate days, which show the model development over a variety of stability and meteorological conditions. The field site at Northolt (grid reference: 51°33′N, 0°25′ W) is an airfield, which is approximately 20 km west of central London and 10 km north of Heathrow airport. Surrounding Northolt the land is fairly flat (40–50 m ASL). The surface properties in the close vicinity of the airfield (within approximately 1 km) are grassland. Away from the airfield there are suburban areas (two-storey housing) to the east, south and north and rural grassland to the west. A map of the area is shown in Davies et al. (2005).

For the first week of the campaign there was a high pressure, high pollution situation with a low mixed-layer height and broken/intermittent stratocumulus clouds. Temperatures reached record high levels, with a maximum temperature of 32.8 °C as measured at Heathrow airport on the 15th July (Weather, 2003). From the 16th July onwards the high pressure was broken down by a series of thunderstorms. By the 19th July more typical low-pressure behaviour had been established with well mixed conditions, cumulus clouds and occasional showers. In this paper, 2 days of data from the first week were analysed (where high pressure and high pollution conditions were prevalent) and 3 days from the last week (where low pressure and cloudy conditions were prevalent).

In Section 2 of this paper, we discuss the set up and formulation of the two models and Section 3 details the determination of the BLH from the lidar data. Section 4 discusses the BLH results.

2. Dispersion models

Validating the boundary layer schemes used by air-quality forecasting models for urban areas is very difficult because of the scarcity of urban meteorological data. In this study, the Met Office UM version 5 (Met Office, 2006; NWP Gazette, 2002a, b) and a dispersion model, ADMS version 3.1 (CERC, 2001), are used to compare with the lidar measurements.

2.1. Unified model

The Met Office UM can be used to input data to run the Met Office's operational dispersion model, NAME. BLH estimates are crucial for the correct modelling of the advection, dispersion and deposition of pollutants (Maryon and Buckland, 1994) and one of the inputs to NAME from the UM is BLH.

The UM boundary layer mixing scheme is a first order closure scheme. It combines a local Richardson-based calculation for stable boundary layers with a non-locally determined K-profile for convective boundary layers (Lock et al., 2000; Martin et al., 2000). For stable boundary layers, a critical Richardson number is used to find the BLH and for unstable boundary layers a moist adiabatic parcel ascent method is employed. In cumulus-capped boundary layers, the convection scheme takes over at cloud base and the BLH is capped at the lifting condensation level (LCL). Through this paper, the UM BLH estimation therefore refers to cloud base or LCL.

The UM has been run in the normal operational manner, which uses synoptic data as inputs to a four-dimensional variational assimilation scheme to blend observations with the previous forecast for initialisation. It has been run with an approximate $12\,km \times 12\,km$ grid resolution and a 3 h time step. The UM has a surface exchange 'tile' scheme that allows several surface types within a grid box (Best et al., 2000).

2.2. ADMS

ADMS is a simple Gaussian-type plume model designed primarily for environmental impact assessment of stacks and for local air-quality management. Spread of a plume is calculated from turbulence profiles modelling the boundary layer and convective profiles are skewed away from Gaussian to recognise the difference between updrafts and down drafts. In this work, ADMS version 3.1 was used. Within the ADMS dispersion model is a meteorological model. This model, the 'met pre-processor' (Thomson, 2000) can accept a range of inputs including surface wind speed and direction, temperature, cloud cover, surface heat flux, specific humidity, albedo and precipitation. Surface characters are also input, such as surface roughness and albedo. BLH is calculated within the 'met pre-processor'.

During this experiment ADMS has been run using hourly surface station data from Heathrow airport. Heathrow airport is situated approximately 8 km south of RAF Northolt. Heathrow airport is a regular synoptic station whose data is checked prior to use within the UK surface synoptic network. ADMS calculates the sensible heat flux, friction velocity, u_*, Monin–Obukhov length scale, L and the convective velocity scale, w_*, amongst other parameters. The sensible heat flux is estimated within ADMS from empirical data using time, position and the other input surface meteorological data.

In ADMS, in stable conditions, the BLH is determined by the method described in Nieuwstadt (1981), where BLH

$$h = \frac{0.3u_*}{|f|}\frac{1.0}{1.0 + 1.9h/L}, \tag{1}$$

where f is the Coriolis parameter. There is a lower limit for L, which is 10 m for urban areas. In neutral conditions, as L becomes very large the BLH is

$$h = \frac{0.3u_*}{|f|} \tag{2}$$

and in unstable conditions the rate of growth of the boundary layer must be calculated.

The sensible heat flux, the friction velocity, the Monin–Obukhov length scale, the convective velocity scale and the BLH are then used to determine the growth rate of the boundary layer. Surface parameters (albedo, surface moisture, roughness length) are also used. The model follows the schemes of Tennekes (1973), Tennekes and Driedonks (1981) and Driedonks (1982), taking the constant values detailed in Driedonks (1982).

Three different settings of ADMS were used to show the sensitivity of results to the input surface roughness length, z_0. The settings correspond to a 'rural' roughness value of $z_0 = 0.1\,m$, an 'urban' roughness of $z_0 = 1.0\,m$ and a 'transition' setting. The transition setting allows two roughness values. This means the value of the roughness at the anemometer position (i.e. wind measurements) may be different from that where the dispersion is to be calculated. This option is designed for the situation where the meteorological data used as input are from an airport, but the pollution dispersion must be calculated over the city. The transition from rural conditions ($z_0 = 0.1\,m$ at the anemometer site) to urban conditions ($z_0 = 1.0\,m$ over the urban site) is therefore simulated.

3. Lidar data

The University of Salford lidar is a pulsed Doppler CO_2 lidar with an operating wavelength at 10.6 μm making it eye safe and ideal for use in urban areas (see Pearson and Collier, 1999). The lidar has a range resolution along the beam of 112 m with a minimum range of approximately 700 m and a maximum range (dependent on atmospheric conditions) of 9 km. The pulse repetition frequency is 10 Hz and the pulses are accumulated to improve the signal-to-noise ratio (SNR), giving a data retrieval rate of approximately 0.2 Hz. Details of the system configuration are given in Bozier et al. (2004), and a discussion of the systematic errors is contained in Davies et al. (2004, 2005).

Doppler lidars use aerosols as tracers for the wind field and measure the along beam component of the wind velocity and backscatter intensity. Vertically pointing backscatter lidars have been used previously to measure mixing layer height and cloud height (Menut et al., 1999; Mok and Rudowicz, 2004). Although the Salford lidar has a relatively large gate length of 112 m, by inclining the beam at shallow elevation angles, the vertical resolution can be increased, (e.g. 20 m at an inclination of 10°) to give sufficient height resolution for mixing layer height determination. The lidar data shown in this paper come primarily from inclined beams at various elevation angles.

The backscatter intensity measured by lidar gives a good measure of the top of the mixing layer because of the large gradient in aerosol concentration between the relatively 'dirty' boundary layer air and the free troposphere air above. This boundary is produced by the capping inversion normally present at the top of the mixing layer. Backscatter intensity can also be used to provide cloud base height because clouds can cause very high backscatter values (Menut et al., 1999).

Backscatter intensity is a function of the system parameters, the reflectivity of the targets, range and atmospheric attenuation. With vertically pointing backscatter lidar, the common procedure is to average the backscatter intensity over some short period of time (1–5 min) and then to plot a profile of the range-squared corrected signal (RSCS) (Menut et al., 1999; Dupont et al., 1994). Data for this study have been corrected in this way. Since the data were also taken during typical summer time, high pressure, high aerosol conditions and at a variety of elevation angles, the profiles are also corrected for atmospheric attenuation.

Atmospheric attenuation is due to atmospheric absorption and particulate scattering. At this wavelength, an extinction coefficient of 1.0 dB km^{-1} is reasonable for mid-latitude summertime clear weather daytime conditions (Rothermel and Jones, 1985). Approximately 0.7 dB km^{-1} of this can be attributed to atmospheric CO_2 and 0.3 dB km^{-1} to the water vapour continuum (Pearson and Collier, 1999).

In this work, the depth of the mixed layer has been estimated by visual inspection (Boers and Eloranta, 1986; Mok and Rudowicz, 2004). Many researchers have produced automated analysis routines to remove the subjectivity of this estimation: Standard deviation method, Menut et al. (1999); gradient method, Flamant et al. (1997); second derivative method, Menut et al. (1999); idealised profiles, Steyn et al. (1999). These different methods, however, work better under some meteorological conditions than others. Using different methods for different conditions implies a prior knowledge of 'what to expect' and, therefore, some subjectivity is still needed for any good diagnosis of the mixing layer height from lidar data. For the work shown in this paper, particular days have been chosen where BLH measurements were numerous and the consistency in the measurements can therefore give an estimate of the validity of the results.

Fig. 1a shows a corrected backscatter profile in a clear sky case. A sharp decrease in the backscatter coefficient, which marks the top of the mixed layer, can be seen at approximately 800 m. In the case of the cloudy boundary layer, shown in Fig. 1b, the high backscatter return signal from the cloud layer

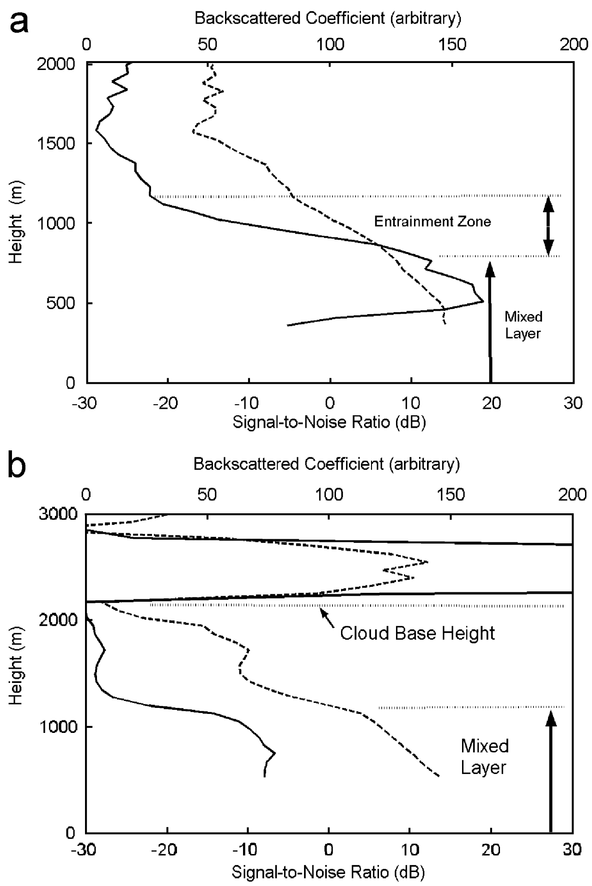

Fig. 1. Profiles of corrected backscatter (line) and signal-to-noise ratio (dashed line) against height. Mixed layer and entrainment zone identified by visual inspection for a (a) a clear sky case on 23/07/03 at 1000 UTC and (b) a cloudy sky case on 23/07/03 at 1700 UTC.

dominates and the cloud base height is seen at a height of 2200 m. As discussed previously, in the UM the BLH in cloudy sky conditions is defined to be the cloud base height or LCL. However, in the data processed during this work, there were several cases where several layers of clouds were evident. In Fig. 1b the cloud base is at approximately 2200 m, but there is a significant decrease in the corrected backscatter at approximately 1200 m, which indicates that the well mixed layer is present only up to this height. For this analysis, we have therefore noted both the cloud base height and the mixed layer height where applicable.

Once the data were corrected for noise, range and attenuation, they were averaged. Each corrected backscatter profile was averaged over 20 pulses (1.3 min). Clear sky sections (as opposed to cloud layers) were chosen where possible to estimate the mixing layer height, and the cloud base height was estimated from the cloudy sections of data.

4. Results and discussion

Five days of data from the Northolt trial have been analysed. Two days of the data (8th and 9th July) were taken prior to the series of thunderstorms, which occurred in the second week of the trial. These days were characterised mainly by the high-pressure/high-pollution levels situated over the area at the time. The next 3 days of data that are shown in this paper were taken from the 21st–23rd July and during conditions that were characterized by predominantly low pressure, convective, showery and fairly clean air conditions.

Fig. 2a shows the mixed layer height and cloud base height as measured by the lidar for 8th July 2003. The plot also shows the BLH as determined by the UM, ADMS 'rural' setting, ADMS 'urban' setting and ADMS 'transition' setting. On this day, all the models over estimate the cloud base height compared with the lidar data. Both the UM and ADMS 'urban' run over estimate the BLH by almost 100%. During the night of the 8th July 2003 a warm front passed over the region of southern England. The BLHs for the 9th July shown in Fig. 2b reflect the increased mixing in the boundary layer that was produced by the front. The steady increase in BLH through the day is captured well by the UM model, but not at all in the ADMS runs.

On the 21st July 2003, after a week of thunderstorms, the trial resumed. The cloud cover was quite extensive and lidar data collection on this day was patchy due to the rain showers (Fig. 2c). Measurements were however possible through the evening transition to 2100 UTC (local sunset was 2110 UTC). Cloud base height measurements from the models show slow BLH growth through the morning due to the cloudy conditions. Lidar measurements agree well with UM, ADMS 'rural' and ADMS 'transition' model runs. The evening transition data also describe well the decrease in the BLH through this period.

The weather on the 22nd July started out much clearer than the previous day with sunshine and only a few patchy clouds, but by midday however the cloud cover was total. The models' boundary layer growth shows this quite well (Fig. 2d), with rapid early morning boundary layer growth, levelling off at 1100 UTC and remaining fairly constant after this time. The ADMS 'transition' run predicts the cloud base height most accurately and the UM and ADMS 'urban' runs over estimate the cloud base height on this day by approximately 20%.

The morning of 23rd July started off with complete cloud cover and the clouds began to clear at approximately 1200 UTC. Fig. 3e shows the slow growth of the morning boundary layer. The ADMS 'transition', ADMS 'rural' and UM reproduce the early morning growth well. The ADMS 'urban' run again over estimates the BLH by almost 100%.

Radiosonde data from three stations (Larkhill: 51.20°N and 1.80°W, Nottingham: 53.00°N and 1.15°W and Herstmonceux : 50.90°N and 0.32°W) surrounding the Northolt site have been used to calculate the LCL using Normand's rule (Wallace and Hobbs, 1977) on a pseudoadiabatic chart. The three radiosonde stations were 125 km west (Larkhill), 200 km north (Nottingham) and 130 km south (Herstmonceux) of the Northolt site. There are no radiosonde stations in or near London for a direct comparison. Fig. 3 shows a comparison of radiosonde LCL with lidar-measured cloud base data. The line of best fit indicates that the lidar data are showing on average a slightly raised cloud base height compared to the radiosonde data. Since all the radiosonde sites were in rural surroundings, the higher cloud base measured at Northolt could be due to urban surface forcings as predicted by modelling studies (Martilli, 2002).

The same procedure has been carried out with the model data. Fig. 4 shows a scatter plot of model BLH, against LCL with the corresponding line of best fit for all the model runs: Fig. 4a UM data, Fig. 4b ADMS 'rural', Fig. 4c ADMS 'urban' and

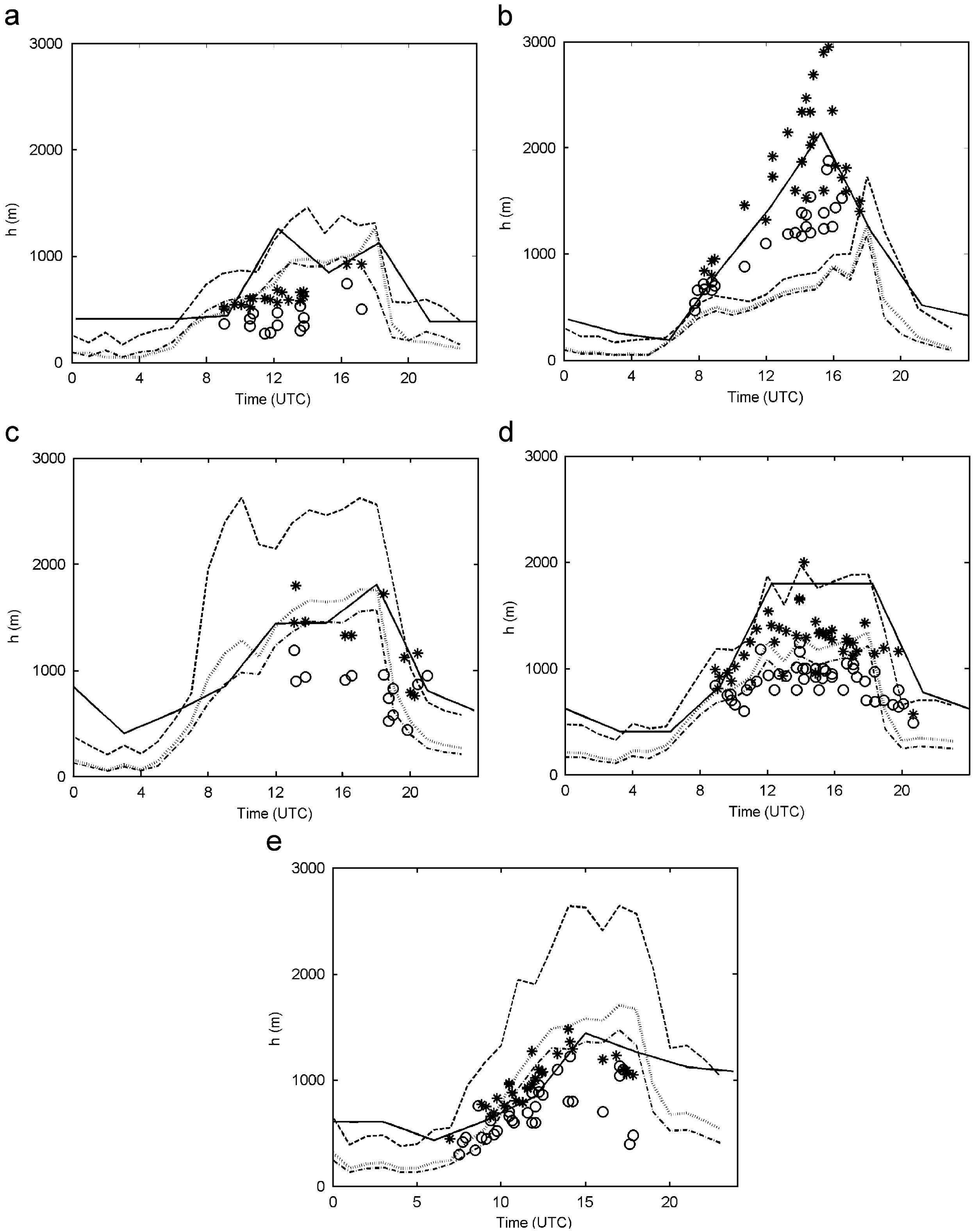

Fig. 2. Boundary layer height, h, against time for the UM model (solid), ADMS 'urban' configuration (dash), ADMS 'rural' configuration (dot–dash), ADMS 'transition' configuration (dotted), lidar mixing layer height (o) and lidar cloud base (*) for: (a) 08/07/03, (b) 09/07/03, (c) 21/07/03, (d) 22/07/03 and (e) 23/07/03.

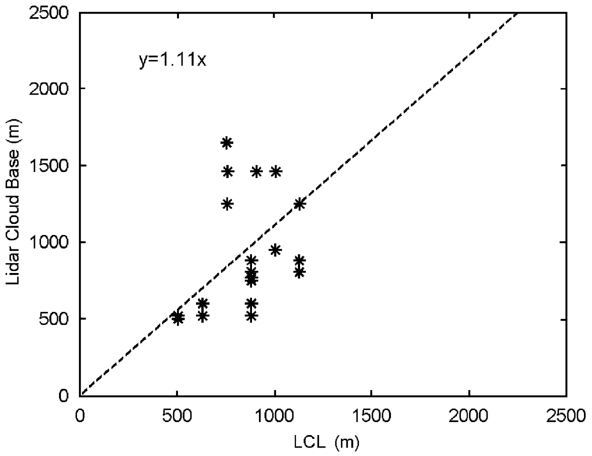

Fig. 3. Scatter plot of lidar cloud base against radiosonde lifting condensation level, LCL. Line of best fit and equation of line also shown.

Fig. 4d ADMS 'transition'. On average, the ADMS 'transition' values (Fig. 4d) give the closest fit to the radiosonde data, although on average the UM data (Fig. 4a) give a fit that is closer to the lidar measurement fit. Both the ADMS 'rural', Fig. 4b and the ADMS 'urban', Fig. 4c show lines of best fit that are not close to unity.

As seen from the discussion above one major factor affecting morning growth of the boundary layer is the cloud cover. Total cloud cover decreases the incoming solar radiation. Surface temperatures then only increase slowly and boundary layer growth is slow, as seen on the 23rd July 2003 (Fig. 2e). The reverse is true on cloud-free days such as 9th July 2003 (Fig. 2b). For the prediction of cloud cover the UM is at a disadvantage in that it is producing its own three hourly cloud cover prediction, whereas ADMS uses the hourly synoptic cloud cover measurements. Consequently in the UM, a poor determination of cloud cover, produces a poor BLH growth forecast that will persist for at least 3 h or until the next time step. The UM run at this 3 h time step is also incapable of reproducing rapidly changing cloud condition such as on the 22nd July (Fig. 2d).

On both the 8th and 22nd July 2003 the UM does a poor job of estimating the cloud base level. Fig. 5a shows temperature anomalies for the 5 days of measurements. For each day the three temperatures (AWS, UM and ADMS) were averaged. The difference from this average is then plotted. The figure shows that, for all the 5 days, the measured automatic weather station, AWS, data from Northolt are cooler by between 1.5–2.5 °C than the measured data from Heathrow airport that was used as input to the ADMS model. This difference is only due to the local conditions of the two sites. UM forecast takes synoptic data from over the UK and is configured to output data for the Northolt position, but Figs. 5a and b show that on the 8th and 22nd July model is both warmer and drier than either of the measured data. These are days on which the modelled boundary layer grows very quickly but the BLH determined from measured data does not. Both the high temperature and low humidity lead to anomalously high heat flux estimates on these days (not shown) and consequently the higher BLH output by the UM model.

On the 9th July (Fig. 2b), ADMS does not capture the rapid growth of the boundary layer. This is despite the input temperature, wind speed, humidity all agreeing with measured AWS data from Northolt (not shown). This day had low wind conditions and the input wind speeds were less than 2.1 m s^{-1} up to 1800 UTC. The ADMS BLH increases very slowly until 1800 UTC. The ADMS 'urban' simulation overestimates the BLHs under all other conditions. This is due to the high roughness length value (1.0 m) used as input to the model in our 'urban' run. Friction velocities estimated by the UM, and measured using a sonic anemometer at Northolt are similar in magnitude to those of the ADMS 'rural' simulation. They range from 0.2 m s^{-1} at midday on the 9th July to 0.8 m s^{-1} at midday on the 21st July. The ADMS 'urban' run has values that are on average almost twice as large. The high friction velocity values dictate greater mixing which produces the higher boundary layer heights in the 'urban' runs.

A problem with using ADMS with the 'urban' roughness setting is that the input wind speeds are from an airfield site with lower surface roughness. The wind speeds are therefore too high and the associated friction velocity too high to represent the flow at the actual dispersion site. This is the reason for using ADMS with the 'transition' setting. A second problem, associated generally with urban modelling, is that roughness lengths are local values and vary greatly over what can be considered as 'urban' surfaces. Grant and Mason (1990) investigated averaged roughness lengths over complex terrain and discuss the associated horizontal scales. In this work, the lidar boundary layer measurements were taken over urban/suburban surface, for

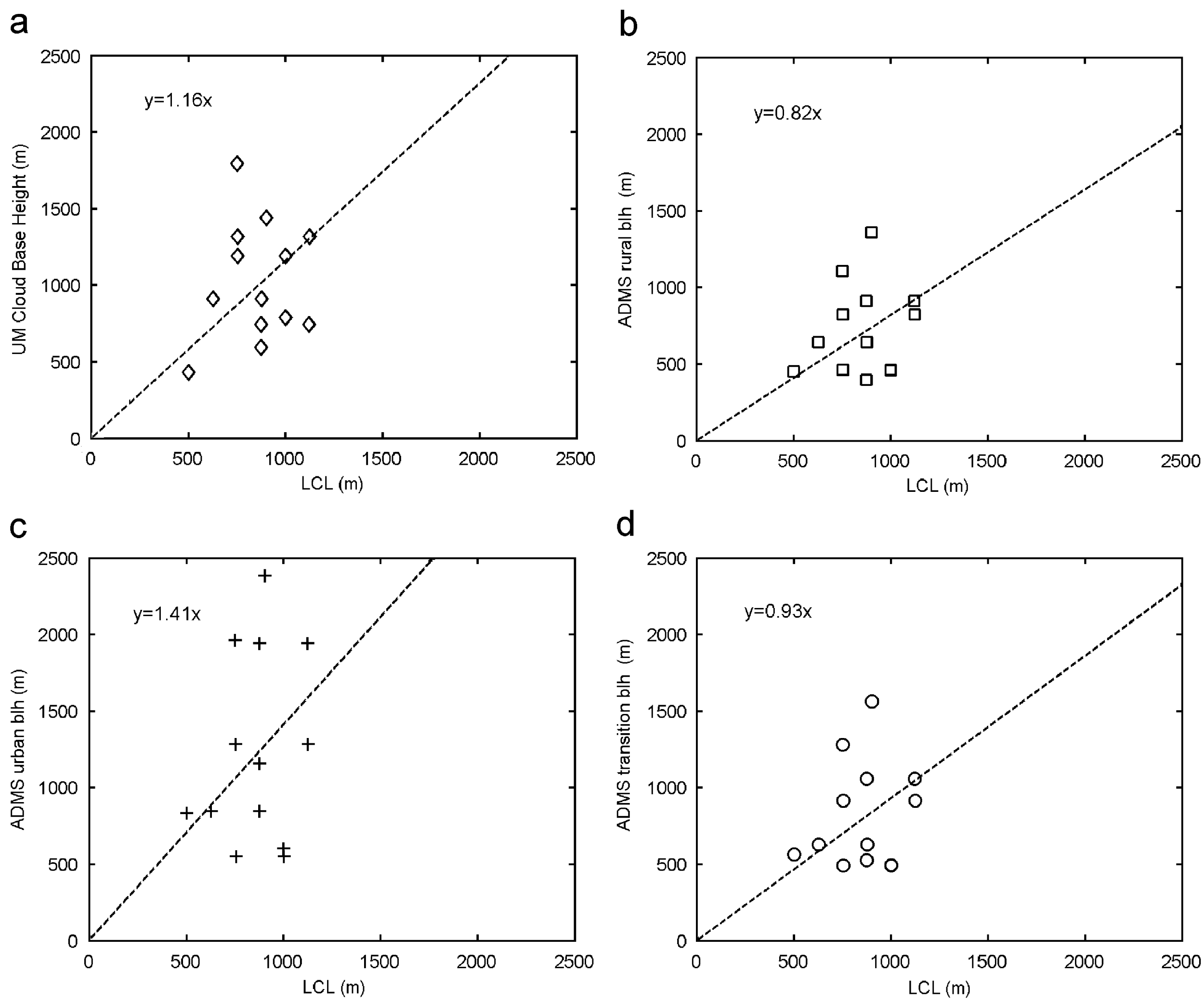

Fig. 4. Scatter plot of model boundary layer height, BLH, against radiosonde lifting condensation level, LCL for: (a) UM cloud-base height, (b) ADMS 'rural' configuration, (c) ADMS 'urban'configuration and (d) ADMS 'transition' configuration. Line of best fit and equation of line also shown.

which a roughness length of 1.0 m was not unrealistic (Grimmond and Oke, 1999). The results show, however, that the values are too large for correct boundary layer growth behaviour. It raises the question of 'over what spatial scale does the roughness length need to be averaged/determined to reflect changes in BLH?'

Another consideration is that the roughness length is not a fixed value for a fixed site. It is itself a function of the stability. So on days that are significantly non-neutral, such as the 9th July, use of the roughness length as an input in prescriptive models such as ADMS does not represent the flow correctly.

5. Conclusions

A trial was undertaken at RAF Northolt within the conurbation of Greater London to validate the BLHs determined by two dispersion models; ADMS and UM. ADMS was run for three particular settings; an 'urban' setting with a surface roughness of 1.0 m, a 'rural' setting with a surface roughness of 0.1 m, and a 'transition' setting. The ADMS 'transition' setting was designed to reflect a measurement site where the input surface roughness was small but where the downwind roughness was large, e.g. a city airport. Doppler lidar data were used to measure cloud base height and mixing level height

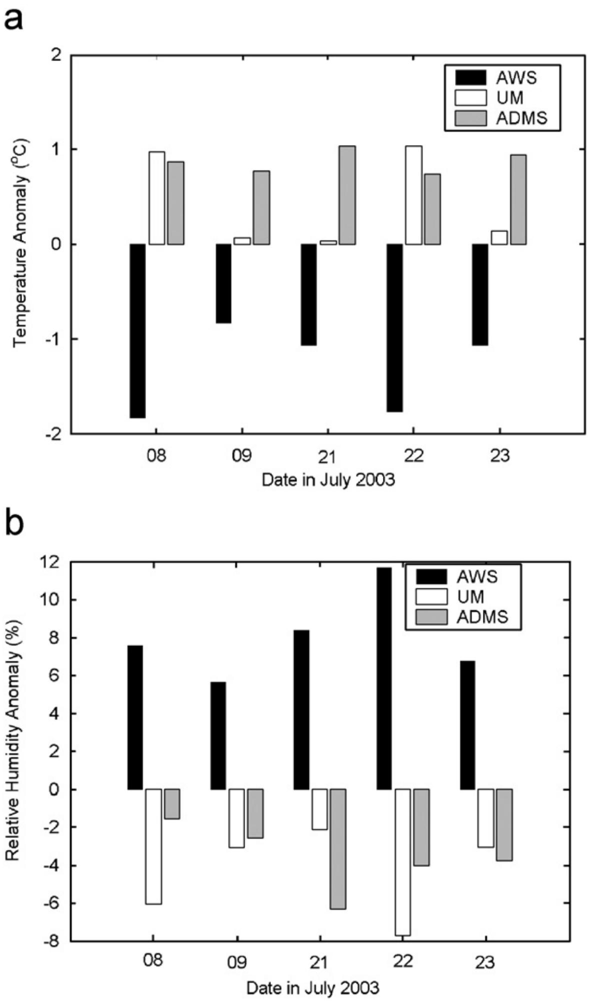

Fig. 5. Anomalies from the 0800 to 1200 UTC mean for the UM, ADMS and AWS averages for: (a) temperatures and (b) relative humidity.

for comparison. Five days of data taken over a 3 week period were analysed. Measured and modelled data were compared against the LCL calculated from radiosonde data. Scatter plots of cloud base height against radiosonde LCL showed that estimates for the cloud base level were best for the UM and ADMS 'transition' models. Lines of best fit for the lidar measurements of BLH against the radiosonde LCL results showed there was a good average correspondence. The ADMS 'urban' run over estimated the BLH by an average of 41%.

Both the growth of the morning boundary layer and dissipation of the evening boundary layer were measured. The UM represented the morning boundary layer growth on very cloudy days (21st and 23rd July) and low cloud cover days (9th July) well, but underestimated the cloud cover and over estimated the surface temperatures on days where the morning cloud cover was variable (8th and 22nd July). The timing of the evening transition was reproduced well in the models.

It is the high-pollution incidents that pose most threat to the health of people in urban areas. July 8th 2003 was one such day. Both the UM and ADMS 'urban' runs on this day showed BLHs that were overestimated by 100%. By over-predicting the BLHs the volume of air through which the pollutants are mixed is greater, and the models will predict pollution concentrations poorly.

The recent COST 715 working group 2 report (Piringer and Joffre, 2005) highlighted the importance of BLH determination for the modelling community. As can be seen from these results, there is much work still to be done to improve the models for simulating the dispersion in urban areas. In this work, an alternative ADMS 'transition' setup was used that gave the best results for these daytime well mixed conditions. This option is already routinely available in the model.

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