Comparison of ADMS 4 and LiDAR in the Prediction of Atmospheric Boundary Layer

by Vera Surtia Bachtiar

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Abstract

Since the late 1950s, atmospheric dispersion models have been developed to predict air quality. The Atmospheric Dispersion Modelling System (ADMS) is a dispersion model that simulates buoyant and neutrally buoyant plumes. Here the model is used to compare modelled and measured boundary layer depth in a city centre where traditionally models are not reliable. Doppler LiDAR (Light Detection and Ranging) can measure basic boundary layer variables, such as mixing depth, wind shear and turbulence, and inversion height. Comparisons are made between ADMS 4 and the Salford LiDAR for data taken in central London on 29 October 2007. On average, boundary layer height predicted by the LiDAR is higher than ADMS 4. The ADMS model has a very simple surface scheme that is not representative of a complex urban environment. The results show that there is not sufficient surface roughness within the model to produce a high enough boundary layer depth. The final aim of this research is to produce a modification to the model to enable the correct simulation of this complex terrain.

Keywords: Boundary layer height, ADMS 4, Doppler LiDAR

1. Introduction

Since the late 1950s, atmospheric dispersion models have been developed to predict air quality (Carruthers, 1994). More than 20 years later, advanced dispersion models have been produced. An example is the Atmospheric Dispersion Modelling System (ADMS). ADMS is used for pollution dispersion modelling in several countries in Europe, Asia, Australia, and the Middle East (CERC, 2008).

In the UK, ADMS was used to review air quality in central London in 1996/1997 and assess future air quality against air quality objectives in 2005 (Colvile et al., 2002). According to CERC (2008), users of ADMS in the UK include over 130 individual company licence holders and regulatory authorities. Amongst them are the UK Health and Safety Executive (HSE), the Environment Agency in England and Wales, the Scottish Environmental Protection Agency (SEPA), the Environment and Heritage Service in Northern Ireland, and government organisations such as the Food Standard Agency.

One of the capabilities of ADMS 4 is the prediction of atmospheric boundary layer properties—most importantly, boundary layer height (BLH). According to Stull (1988, p.2), boundary layer is "that part of the troposphere that is directly influenced by the presence of the earth's surface and responds to surface forcing with a timescale of about an hour or less."

BLH is one parameter of the meteorological data that is required in the meteorological pre-processor in the ADMS model. It is an important parameter in dispersion models because determines the location and transport of aerosols and pollutants. BLH also will determine the volume available for pollutant dispersion, depending on meteorological parameters, surface turbulent fluxes, and physical parameters (Fisher et al., 2005). The limits on the vertical diffusion of the plume or puff of material released are also determined by BLH. In urban air quality modelling, BLH is influenced by the vertical profile of mean wind velocity and the turbulent vertical exchange of momentum, heat, and moisture (Dandao et al., 2009).

The accuracy of BLH is important in urban air quality modelling because it affects near-surface pollutant concentrations (Dandao et al., 2009). BLH estimation is different in different models. An example of different BLHs calculated by ADMS 3.1 and AERMOD PRIME 02222 was shown by Sidle et al. (2004). They found that the pollution concentration differences between the two models could be attributed to the differences in the derived BLHs. In this paper, we carried out prediction of the atmospheric boundary layer (BLH) depth using the ADMS 4 model and compared it to measurements from LiDAR aerosol backscatter data.

2. Atmospheric boundary layer

The atmospheric boundary layer is part of the troposphere. The troposphere consists of a boundary layer and free atmosphere, as shown in Figure 1. The boundary layer's thickness is variable from as low as 100 metres to 2–3 kilometres. This depends on several factors, including evaporation and transpiration, frictional drag, heat transfer, pollutant emission, and terrain-induced flow modification. The height of boundary layer is not constant with time and depends on the strength of the surface-generated mixing. In the daytime, when the earth's surface is heated by the sun, there is an upward transfer of heat from the surface to the atmosphere. In contrast, at night-time, the Earth's surface cools more rapidly than the atmosphere (Oke, 1987).

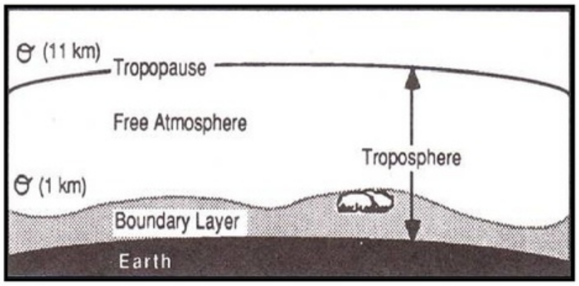

Figure 1. Troposphere and atmospheric boundary layer.

Source: Stull (1988)

The diurnal cycle depth of the boundary layer over land surfaces can be seen in Figure 2. The major components of the structure are the mixed layer, the residual layer, and the stable boundary layer.

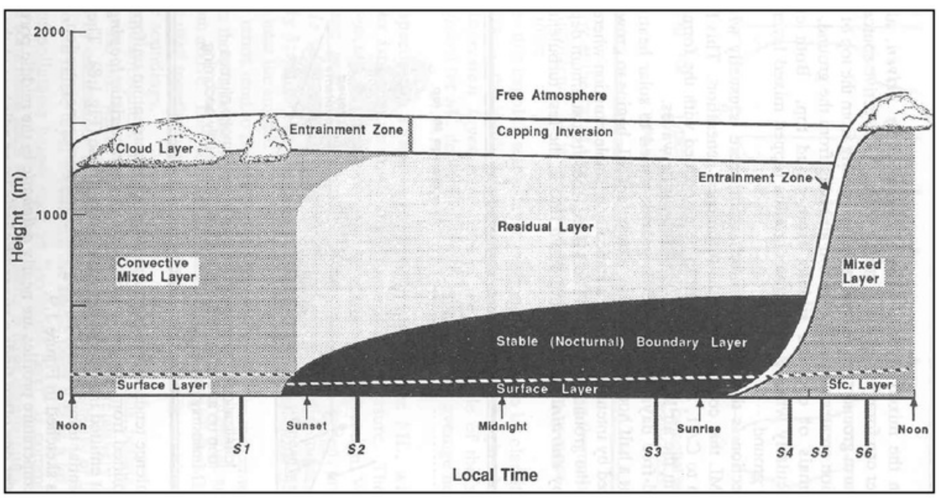

Figure 2. Structure of the atmospheric boundary layer.

Source: Stull (1988)

On a cloud-free day, after about one hour after sunrise, thermally driven mixing begins. In this condition, thermals of warm air rise from the ground. As the surface heats up through the morning, this well-mixed layer grows in height, causing an increase in the depth of the statically unstable layer. In the late afternoon, the mixed layer reaches its maximum depth. Because of the turbulence, the characteristics of the mixed-layer heat, moisture, and momentum profiles are constant in the vertical direction. In the middle of the mixed layer, virtual temperature profiles are nearly adiabatic, but in the surface layer they tend to be super-adiabatic. At the top of the mixed layer, a stable layer is present that limits the height to which the thermals rise. The height of this level is defined as the BLH. The zone between the well-mixed layer and the free troposphere is called the entrainment zone, because in this zone entrainment into the mixed layer occurs (Stull, 1988).

About one hour before sunset, turbulence decays in the previous well-mixed layer. The layer has pollution concentrations similar to those of the previous well-mixed layer. This layer is called the residual layer and has neutral turbulence and equal intensity in all directions (Stull, 1988).

In the night-time, the bottom portion of the residual layer transforms into a stable boundary layer by its contact with the ground. This layer is characterised by statically stable air with weaker and sporadic turbulence. Although surface winds are calm at night, the winds aloft increase rapidly and form a low-level jet or nocturnal jet. This nocturnal jet tends to generate turbulence, so that sometimes turbulence occurs in the stable boundary layer (Stull, 1988).

3. Atmospheric dispersion models

Atmospheric dispersion models are computer programs using mathematical algorithms to simulate pollution dispersion in the atmosphere. They have been developed since the late 1950s. Most dispersion models use a Gaussian dispersion process and meteorological surface measurement (Carruthers, 1994). An illustration of Gaussian dispersion process (the Gaussian Plume Model) is provided in Figure 3.

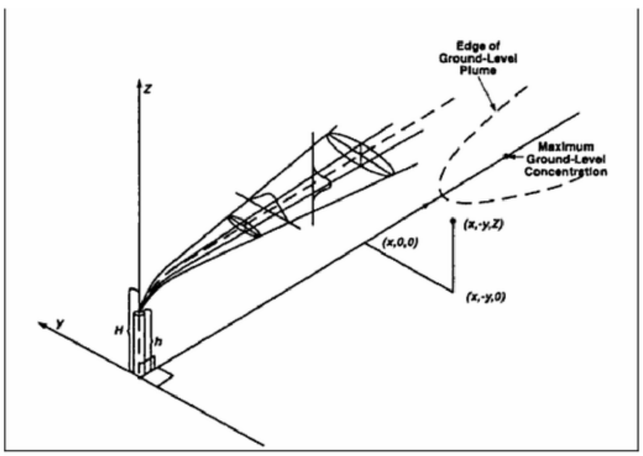

Figure 3. Gaussian Plume Model.

Source: Water Environment Federation, American Society of Civil Engineers, Water Environment Federation. Liaison Subcommittee (1995)

Gaussian models are based on a Gaussian distribution of the plume in the vertical and horizontal directions under steady-state conditions. The normal distribution of the plume is modified at greater distances due to the effects of turbulent reflection from the surface of the earth and at the boundary layer when the mixing height is low (Holmes and Morawska, 2006). The width of the plume is determined by the standard deviation of the concentration distribution in the crosswind direction (σ_y) and the standard deviation of the concentration distribution in the vertical direction (σ_z) (Turner, 1994).

Over the past 20 years, better and better models have been developed. Current models use a new approach—namely, the vertical profile of mean velocity, temperature, and turbulence in the boundary layer above the ground; the height of the boundary layer h; and the Monin-Obukhov length L_{MO} (Carruthers, 1994).

Atmospheric dispersion models have been developed in the United States, the United Kingdom, continental Europe, and Australia. The models range from screening models to advanced models. The U.S. Environmental Protection Agency's (EPA) list of recommended models includes the AERMIC MODEL (AERMOD), CALPUFF, BLP, CALINE3, CAL3QHC and CAL3QHCR, CTDMPLUS, and OCD. Other models include the Air Force Dispersion Assessment Model (ADAM), the Atmospheric Dispersion Modelling System (ADMS), Industrial Source Complex (ISC3), and the Air Force Toxics Model (AFTOX). Some of the models that are used in the United Kingdom are GASTAR, NAME, UDM, ADMS-screen, ADMS 3, ADMS-URBAN, ADMS-roads, and ADMS 4 (the newest).

4. ADMS 4

Atmospheric Dispersion Modelling System (ADMS) is a dispersion model that simulates buoyant and neutrally buoyant particles and gasses (Carruthers et al., 1994). The model can predict the boundary layer structure. It uses normal Gaussian distributions in a stable and neutral condition (Holmes and Morawska, 2006). ADMS was developed by a government and industry consortium in the UK (CERC, 1998; in Hana et al., 2001).

As illustrated in Figure 4, ADMS can simulate a number of processes. The figure shows a number of model processes. Firstly, ADMS 4 can model dry and wet deposition. It can assume dry deposition to the near-surface concentration. Wet deposition is modelled through a washout coefficient, irreversible uptake is assumed, and plume strength following wet deposition decreases with downwind distance. Secondly, ADMS 4 also can model continuous (i.e., plumes and time-dependent) release (i.e., puff). Thirdly, ADMS 4 can model the variation of the emission rate with time, building effect, complex terrain, and coastlines. The model can include up to 25 buildings in each run. For running coastlines, the model assumes that the sea is lower than the land, that there are convective meteorological conditions on the land, and that there is onshore wind. Furthermore, ADMS 4 can model the dispersion of odour and predicts the decay of radioactive (and gamma dose) species released from a source. Finally, ADMS 4 can model a simple NO_x chemistry scheme involving the conversion of Nitrogen Dioxide (NO_2) to Nitrous Oxide (NO) and Ozone (O_3).

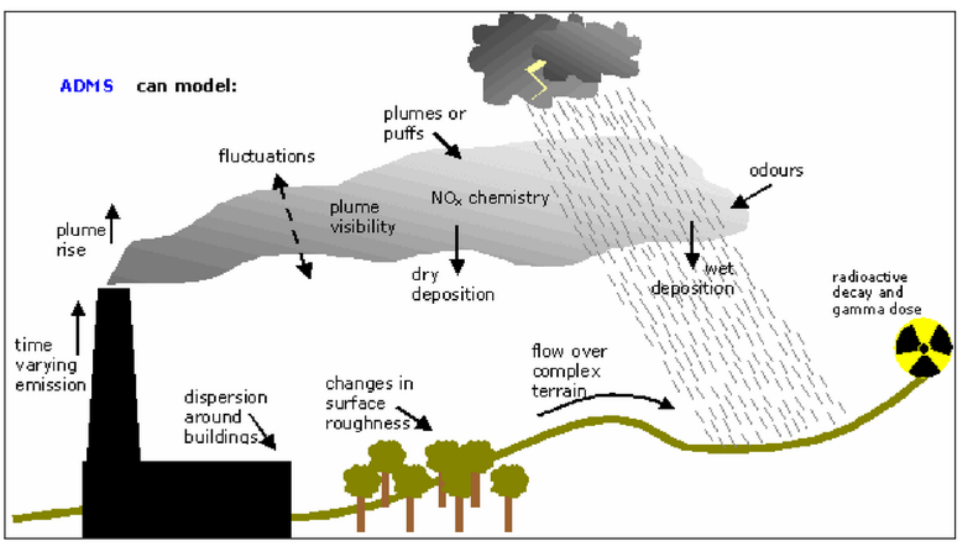

Figure 4. Processes that can be represented by ADMS.

Source: CERC (2008)

5. Salford Doppler LiDAR

Doppler LiDAR (Light Detection and Ranging) is an instrument that transmits pulses of light from a laser to the atmosphere, which are then reflected from aerosols suspended in the atmosphere. This weakly reflected signal is collected by telescope. The distance from which the reflection occurs is calculated by relating the speed of light to the timing of the transmitted and received pulses (Koch, 2009). A pulse or pulses of light are transmitted by the LiDAR system, and then the backscatter signal or intensity of the return signal is received back at the receiver. The backscatter signal or intensity is analysed by the LiDAR system as a function of time. A LiDAR can measure basic boundary layer variables, such as aerosol backscatter coefficient and depolarisation ratio, longitudinal (along the beam) wind component, water vapour density, temperature, and concentrations of some other constituents. From these basic measurements, other boundary layer parameters can be calculated, such as mixing depth, wind shear, inversion height, and aerosol type (Schwielsow, 1986).

The Salford Halo Doppler LiDAR (Figure 5) is an autonomous instrument for atmospheric remote sensing that operates at a wavelength of 1.5 microns. It employs novel optical technology, is designed to be eye-safe class 1M, and has low power. The system has three separate units: the optical base unit, the weatherproof monostatic/antenna, and the signal-processing and data-acquisition unit. The optical base unit has dimensions of 0.56 m × 0.54 m × 0.18 m, and contains the optical source, interferometer, receiver, and electronics. The weatherproof antenna is connected to base unit using an umbilical. The antenna can be placed in outside, whilst the base unit and data-acquisition system are housed within a laboratory environment or environmental container (Bozier et al., 2007).

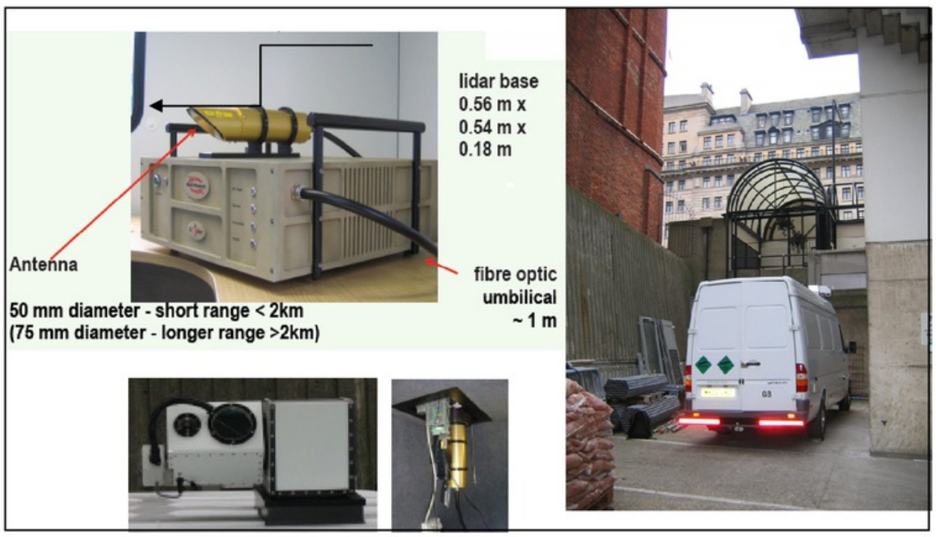

Figure 5. Salford Halo Doppler LiDAR.

Source: Davies et al. (2008)

The system parameters of the Salford Halo Doppler LiDAR can be seen in Table 1. The parameters—such as range gate, maximum range, number of pulses accumulated for each measurement, and the temporal resolution of the Doppler measurements—can be set by the user. The LiDAR system can be monitored and controlled by remote access software that transfers data using an internet network connection (Bozier et al., 2007).

Table 1. The Salford Halo Doppler LiDAR parameters.

Parameter	**Value**
Operating wavelength	1.55 μm
Pulse repetition frequency	20 kHz
Pulse duration	150 ns
Beam divergence	50 μrad
Range gate	Variable: 20-60 m
Minimum range	~50 m
Maximum range	7 km
Temporal resolution	0.1-30 s

Source: Davies et al. (2008)

6. Results and discussion

Comparison was made between ADMS 4 and Salford LiDAR on 29 October 2007. The input surface meteorological data for ADMS 4 were obtained from the Met Office. Because no surface meteorological data is available from central London, data was used from several locations close to where the LiDAR data was measured. These locations are Andrewsfield, Charlwood, Heathrow, and Northolt, as shown in Figure 6. The LiDAR data was taken by the University of Salford pulsed Doppler LiDAR, which was based at the University of Westminster on Marylebone Road in London. These locations can be seen in Figure 6.

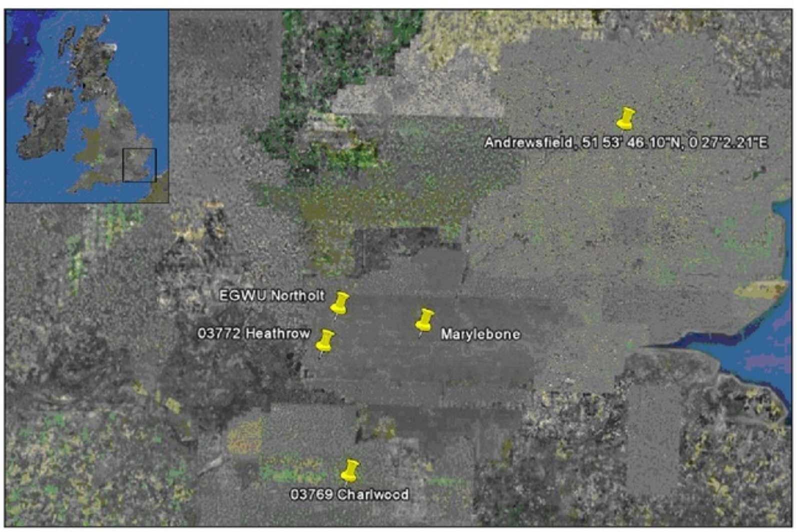

Figure 6. Location of study.
Source: Google Earth (2009)

The boundary layer heights predicted by ADMS and measured by the LiDAR on 29 October 2007 can be seen in Figure 7. This figure shows that boundary layer heights measured by the

LiDAR are higher than those predicted by ADMS 4. In the daytime, in well-mixed conditions, the highest boundary layer heights shown by the LiDAR data was 1230 m, and ADMS predicted the highest boundary layer height to be 846 m. During the night-time, there is an assumption within ADMS that the boundary layer collapses to a stable nocturnal layer. In these cases, ADMS assumes a constant MHL of 100 m, as shown in Figure 7. In urban areas, however, the night-time boundary layer can still contain mixing driven by anthropogenic heating and turbulent mixing of the flow around the buildings. The LiDAR MLH measurements are affected by both of these factors, but are also determined by the aerosol in the atmosphere, which can persist even without mixing in the residual layer. For this reason, the night-time predictions of the BLH are too low from ADMS and if a residual layer is present, the measurements of the LiDAR BLH could be too high. This phenomenon can be seen after 16 UTC, when the boundary layer height decreases in ADMS while LiDAR prediction remains constant through most of the evening.

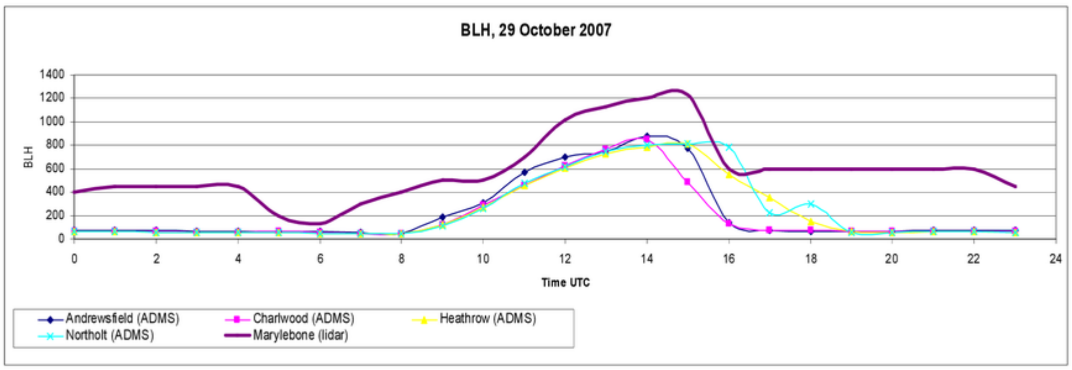

Figure 7. Boundary layer height (BLH) on 29 October 2007.

Correlations between ADMS 4 and LiDAR in the daytime are shown in scatter plots in Figure 8. The figure shows scatter plots of ADMS 4 predictions (for Andrewsfield, Charlwood, Heathrow, and Northolt) against LiDAR data (in Marylebone). The figure shows large amounts of scatter. The 1:1 correlation between ADMS 4 and LiDAR data is shown by the 45° lines in the figure. These showed that ADMS 4 values in all locations are equal to about half those of the LiDAR data values.

The difference in BLH from ADMS and LiDAR can be due to different factors. Firstly, meteorological input used in ADMS 4, such as wind speed, was from a meteorological station outside of the city, where there was lower surface roughness (Davies et. al., 2007). Furthermore, ADMS 4 has a very simple surface scheme, which is not representative of a complex urban environment. The results show that there is not sufficient surface roughness within the model to produce a high enough boundary layer depth.

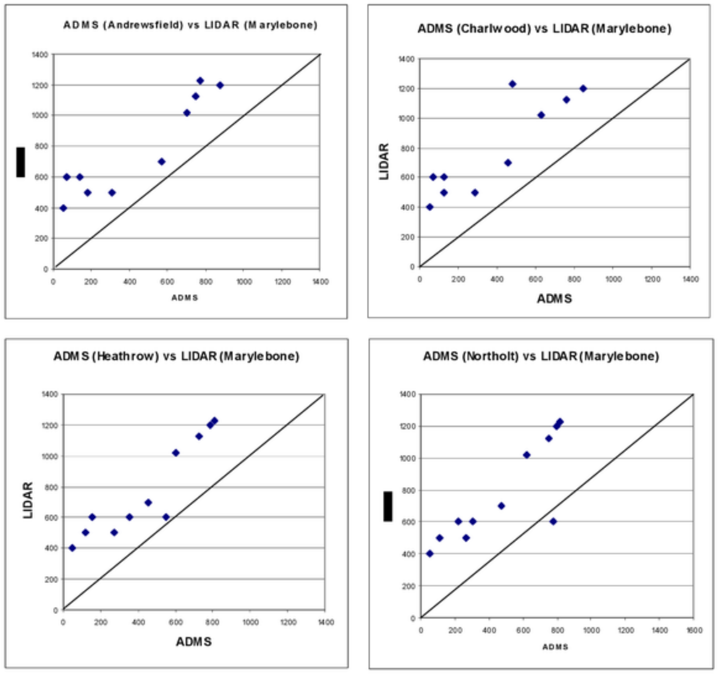

Figure 8. Correlation between ADMS 4 and LiDAR data in the daytime.

A comparative statistical analysis has been carried out between ADMS 4 and LiDAR. Table 2 shows coefficient of determination (R^2) and percentage difference between ADMS 4 and LiDAR. The coefficient of determination represents the percent of the data that is the closest to the line of best fit. These data shows R^2 values between 0.70 and 0.85, with an average value of 0.79. Meanwhile, percentage difference between ADMS 4 and LiDAR is between 43% and 60%, with an average of 51%. This means that ADMS 4 and LiDAR data have good correlations in pattern, but both have large differences in value—namely, all ADMS 4 data is underestimated, in contrast to LiDAR data.

Table 2. Statistical analysis.

ADMS locations	R^2 (Coefficient of determination)	% difference with LiDAR
Andrewsfield	0.85	54 %
Charlwood	0.77	60 %
Heathrow	0.85	47 %
Northolt	0.70	43 %
average	**0.79**	**51 %**

7. Conclusion

Comparison between ADMS 4 and LiDAR data was carried out on central London data on 29 October 2007. Meteorological data for ADMS 4 was obtained from the Met Office for four meteorological stations: Andrewsfield, Charlwood, Heathrow, and Northolt. LiDAR Data was taken by the University of Salford pulsed Doppler LiDAR, which was based at the University of Westminster on Marylebone Road in London.

The comparison shows that the boundary layer height (BLH) predicted by the LiDAR is higher than that predicated by ADMS 4. There is a lot of scatter in the data. This can be due to many different factors, including meteorological variables and surface roughness. Finally, ADMS 4 has a very simple surface scheme that is not representative of a complex urban environment. The results show that there is not sufficient surface roughness within the model to produce a high enough boundary layer depth.

Further work will aim to develop a surface model to improve the estimation of BLH from ADMS and thereby enable the correct simulation of this complex urban environment.

Acknowledgments

This study is funded by the Indonesian government's Directorate General of Higher Education. We also acknowledge the Met Office of the United Kingdom for providing us with the meteorological data for running ADMS 4.

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