Weather and Climate ***24 (2005)***, *3-14*

THE INFLUENCE OF LOCAL SURFACE WINDS ON AIR POLLUTION CONCENTRATIONS AT CURBSIDE MONITORING STATIONS AND ITS CONSEQUENCES FOR MODELLING

Kim N. Dirks[1*] and Andrew P. Sturman[2]

[1] The University of Auckland, Private Bag 92019, Auckland, New Zealand
[2] University of Canterbury, Private Bag 4800, Christchurch, New Zealand

Abstract

This paper investigates the surface wind variations at a suburban air quality monitoring station located in Hamilton, New Zealand and its impact on air pollution levels. Site-specific wind speed and direction information is found to be important, due to valley winds generated by a nearby basin of the Waikato River that passes through Hamilton City. Wind shifts due to the resulting valley winds were seen to lead to 180º wind direction changes that frequently coincide with the peak morning traffic and hence peak air pollution concentrations. This suggests that attempts at modelling vehicle-generated pollution need to either incorporate the valley winds into the model (with accurate representations of the timing of the wind shifts) or use wind information collected at the site. The results of a semi-empirical model presented here suggest that hourly averages are adequate for predicting pollutant concentrations, even under conditions such as those experienced in Hamilton where there are significant wind direction shifts at peak traffic times.

1. Introduction

In New Zealand cities, the motor vehicle is a major source of atmospheric pollution. For this reason, many air pollution monitoring stations are located adjacent to busy roads in urban centres. The observed concentrations at these sites are determined by traffic flow patterns, vehicle emission rates, and by the prevailing atmospheric

* *Corresponding Author: Dr. Kim N. Dirks, Department of Physiology, Faculty of Medicine and Health Sciences, The University of Auckland, Private ionBag 92019, Auckland, New Zealand.*
Phone: 64-09-373-7599 Ext: 86301, Fax: 64-09-3737-499 Email: k.dirks@auckland.ac.nz

conditions in the immediate vicinity of the site. Among these, the wind speed and direction, together with the thermal structure of the atmosphere, affect the distribution of pollutants, while both the topography and the surface roughness near the road influence the effect that meteorology has on the dispersion processes. The mechanically generated turbulence created by the passage of vehicles can also strongly affect the nature of the dispersion (Eskridge and Rao, 1986, and Gronskei, 1998).

This paper investigates the surface wind variations at a suburban air quality monitoring station located in Hamilton, New Zealand, affected by valley winds associated with a river basin located half a kilometre away from the monitoring site. In particular, wind shifts of 180° often occur during times of peak morning traffic and hence peak air pollution concentrations. Given the impact of these wind shifts on pollution levels, the purpose of this paper is to investigate the impact that these wind shifts could have on air pollution model performance and its implications for the choice of averaging times under such conditions, as both ten-minute and hourly averages are commonly used in air pollution modelling studies.

Figure 1. Location of Hamilton within New Zealand and map of the area surrounding the suburban monitoring site. The symbol represents the location of the sampling site.

2. Data

Hamilton has a population of about 117 000 people and is the fourth largest urban centre in New Zealand. It is the main New Zealand centre located inland and is positioned in a shallow basin in which temperature inversions regularly occur, particularly in winter, leading to higher pollution levels at this time of the year. Environment Waikato[1] established a suburban air quality monitoring station in 1997. The site is located in the northeast corner of an actuated four-way traffic light intersection, approximately 10 m from the edge of Peach Grove Road (running north-south) and 85 m from Ruakura Road (running east-west). The site is approximately 500 m east of the Waikato River valley that passes through Hamilton City in a northwesterly-southeasterly direction. Figure 1 shows the location of Hamilton within New Zealand, as well as a map of the area showing the river and the location of the air quality monitoring station.

The data archive for the site used in this study consists of carbon monoxide concentrations, and wind speed and direction. All are logged as ten-minute averages. Wind speed and direction are measured at a height of 5 m above ground level using an anemometer and a wind vane fixed to a meteorological tower. The anemometer has a threshold wind speed of 0.15 m s^{-1}. The carbon monoxide monitor is housed inside an air-conditioned trailer with inlets also set at approximately 5 m. The carbon monoxide monitor used is a non-dispersive infrared photometer monitor approved by the USEPA as a standard monitoring device at the time when the measurements were taken. Data for this study were collected from December 1997 to July 1998, with meteorological data collected for a complete year.

Figure 2 shows ten-minute average carbon monoxide concentrations for the suburban site, for the summer (December to March) and autumn (March to June) seasons. On average, the concentrations tend to peak around 0.7 ppm during summer and around 1.6 ppm during autumn mornings and evening rush hours. The higher average autumn concentrations are consistent with the lower average wind speeds ggenerally found during this time of the year (concentration is related to the inverse of tthe wind speed). Note the sharp increase in average concentration observed around

---

[1]. The local body responsible for monitoring and regulating the environment in the Waikato Region.

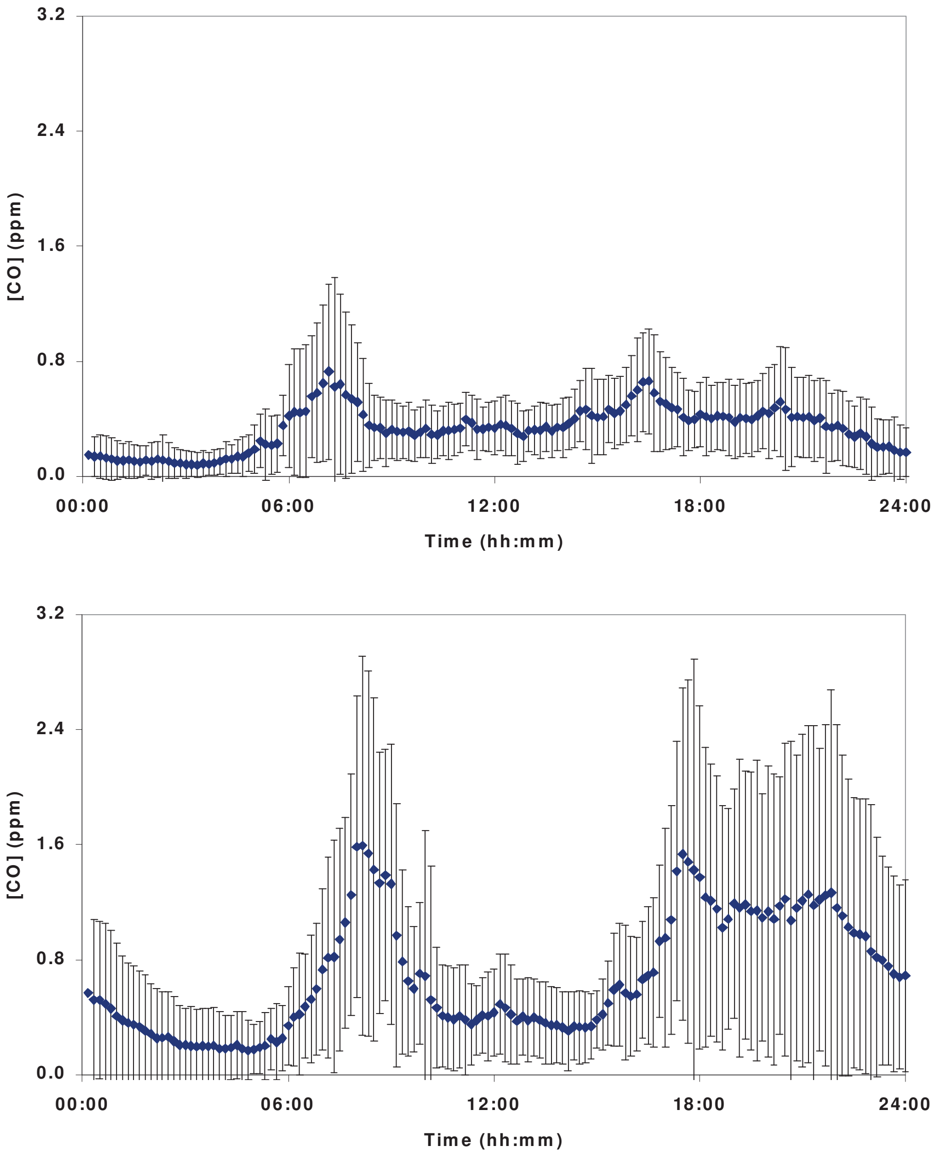

Figure 2. Ten-minute average carbon monoxide concentration throughout the day for the suburban site for summer (top) and autumn (bottom).

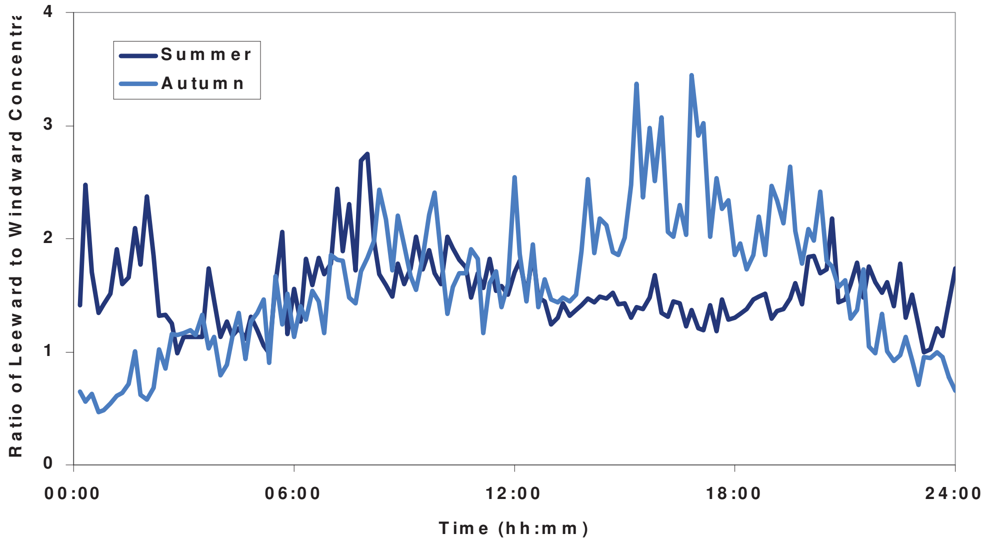

Figure 3. The ratio of the average leeward to windward CO concentration for the summer and autumn.

8:00, consistent with the rapid increase in traffic densities at this time of day during weekdays.

Wind direction also has an impact on air pollution levels for urban monitoring stations located next to roads. It is expected that higher concentrations occur when the wind is such that the monitor is leeward of the road, compared to windward. Figure 3 shows the ratio of the concentration for leeward time periods relative to windward time periods for the two seasons, averaged over the 60 days of weekday data for the two seasons from the one carbon monoxide monitor. Note that for both seasons, the concentrations for leeward wind conditions tend to be about twice those of windward conditions (a ratio of about two) during morning rush hour and about 1.5 to 2.5 for the evening rush hour. Therefore, the data suggest that wind direction (at least the distinction between leeward and windward wind conditions) has a significant effect on pollutant concentrations for curbside monitoring stations and needs to be considered when predicting pollution concentrations based on traffic flows and meteorology.

In Hamilton, the shallow river valley that runs through the city results in a downslopeupslope local wind system on some days when the synoptic winds are light (note that the prevailing winds are westerly). As the monitoring station is located to the east of the river basin, this results in easterly local winds at night (flows towards the river basin).

Shortly after sunrise, after surface heating has helped to warm the air in conditions of light winds (when air pollution levels tend to be high), a shift in wind direction from easterly to westerly is quite common. For the site in question, this morning wind direction shift has been found to be noticeable for 27, 14, 21 and 35% of the days during the summer, autumn, winter and spring seasons, respectively. Figure 4

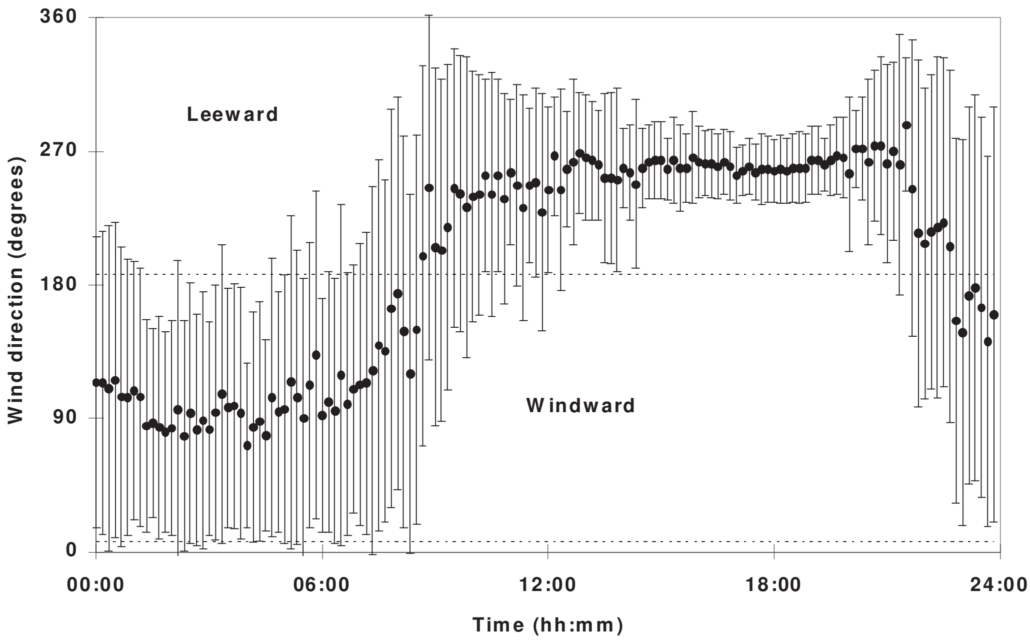

Figure. 4. The mean wind direction at the Peach Grove site when the wind showed shifts in direction due to slope winds.

presents the average wind direction for the days that demonstrate this wind shift. Note that the shift in the wind from the monitor being on the windward side of the road to the leeward side of the road tends to occur around the time of the morning rush hour. The exact timing of the shift on a particular day (depending on the time of year and incoming radiation) will affect the morning peak carbon monoxide concentration, with higher peaks being observed when the shift occurs earlier (all else being equal) because of the location of the monitor relative to the road.

Clearly, a model for predicting air pollution concentrations will need to consider whether the wind direction is such that the monitor is windward or leeward of the road, in order to make realistic concentration estimates. It is expected that the choice of an hourly averaging time will have a significant impact on model performance compared to a ten-minute averaging time, as the latter would better represent the timing of the wind shift.

In the following section, a simple semi-empirical model for predicting carbon monoxide concentrations is described. The model is used to investigate the impact of averaging time on model predictions of air pollution levels in such an environment.

3. Model description

The semi-empirical model is based on the box model approach, where the emission rate Q (mg m^{-1} s^{-1}) is assumed to be constant along a road and the pollutants are mixed uniformly within a two-dimensional box of height Δz (m) (Hanna, Briggs and Hosker, 1982). The horizontal wind speed, u (m s^{-1}), assumed to be uniform within the layer and running perpendicular to the road, removes the pollutants through advection. At the same time, pollutants are introduced into the box through advection of the background concentration. Providing the wind is such that the monitor is leeward of the road, the concentration C (mg m^{-3}) under steady-state conditions is given by

$$C = \frac{Q}{\Delta z (u + u_o)} + C_B \quad (1)$$

where the background concentration is given by C_B (mg m^{-3}). The wind speed offset, u_o (m s^{-1}) is included to avoid severe over-predictions in very light wind speed conditions. A similar function is assumed for windward conditions.

The optimum value for u_o was determined empirically through the minimization of the

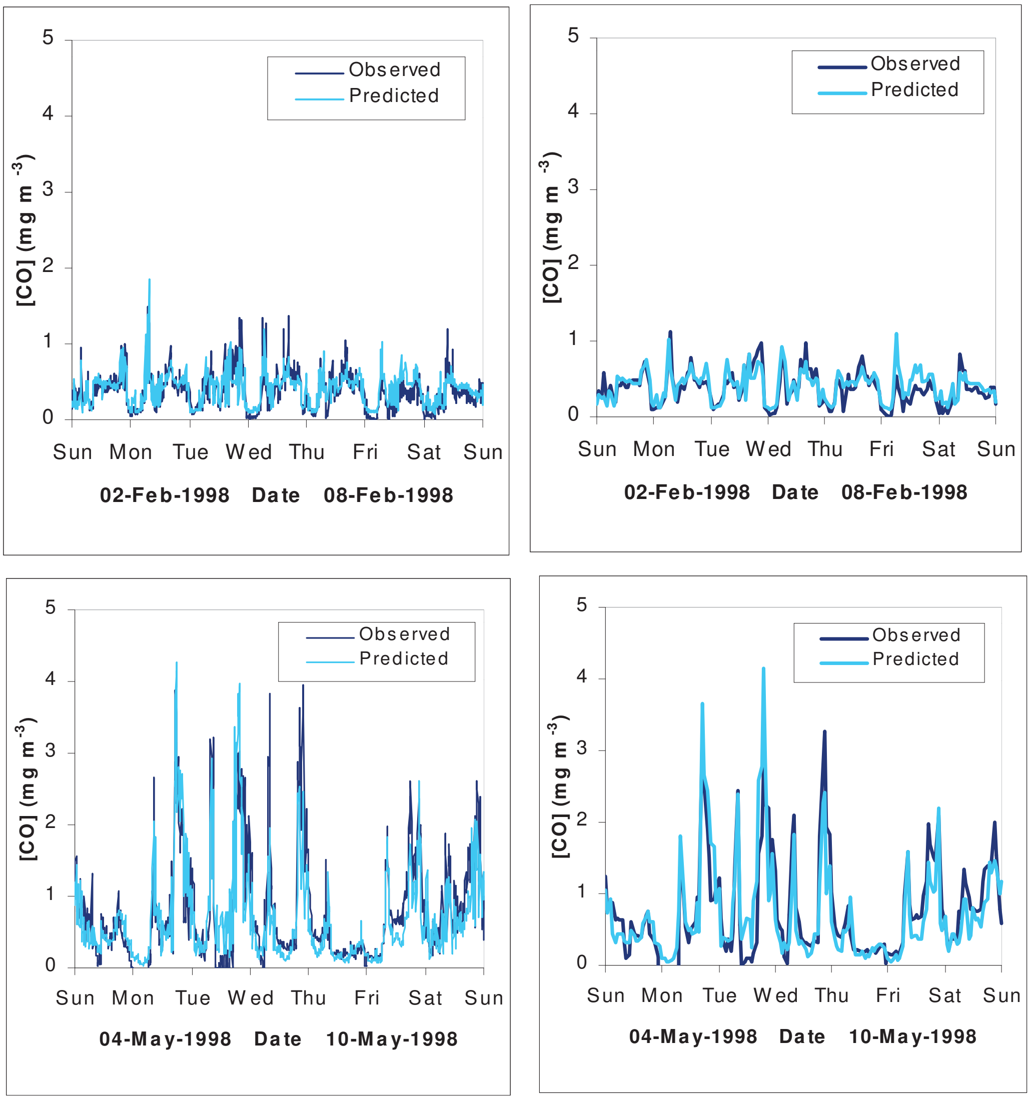

Figure 5. Example of one week of model predictions for the summer season (top) based on ten-minute averages (left) and hourly averages (right), and for the autumn season (bottom) based on ten-minute (left) averages and hourly averages (right).

model root-mean-squared error (RMSE). Optimum model parameters ($Q \triangle z^{-1}$ and C_B) were found by performing linear regressions of carbon monoxide concentration (C) on the wind speed function $(u + u_0)^{-1}$ for leeward and windward conditions separately for each ten-minute interval throughout the day, and across all days in the data set. Weekend data were treated separately from weekday data, as traffic flow patterns were expected to be significantly different. In both cases, the optimum parameters were constrained to avoid negative concentration predictions. Data were also sorted by season to take into account the seasonal variations in meteorology. More details of the model can be found in Dirks *et al.* (2001). Model optimum parameters and model predictions were made based on both the original ten minute average data, as well as hourly average data.

4. Model results

Figure 5 shows examples of one-week time series of observed and model predicted concentrations. Figures 5a and b are for the summer season based on ten-minute averages and hourly averages, respectively, while Figures 5c and d are for the autumn season based on ten-minute averages and hourly averages, respectively. Note that the model performs quite well and the matches between observations and predictions appear to be comparable whether based on hourly or ten-minute averages. Table 1 shows model performance statistics for the two seasons and the two

	Summer		**Autumn**	
	10 Minute	**Hourly**	**10 Minute**	**Hourly**
Mean Obs	0.350	0.350	0.619	0.623
Mean Pred	0.351	0.351	0.629	0.632
(mgm^{-3}) MBE (mgm^{-}	0.001	0.001	0.009	0.009
MAE (mgm^{-}	0.121	0.108	0.285	0.253
^{3}) RMSE	0.176	0.148	0.464	0.398

Table 1. Table of model performance statistics for hourly averaging and 10-minute averaging. Mean Obs is the mean of the observed concentration, Mean Pred is the mean of the predicted concentrations, MBE is the mean bias error, MAE is the mean absolute error, and RMSE is the root-mean-squared error.

	Summer				Autumn			
	10 Minute		Hourly		10 Minute		Hourly	
	Shift	No Shift	Shift	No Shift	Shift	No Shift	Shift	No Shift
Mean Obs (mgm^{-3})	0.49	0.44	0.49	0.44	0.91	0.86	0.91	0.86
Mean Pred (mgm^{-3})	0.49	0.45	0.47	0.45	0.94	0.86	0.94	0.88
MBE (mgm^{-3})	0.00	0.00	-0.02	0.01	0.04	0.01	0.04	0.01
MAE (mgm^{-3})	0.18	0.20	0.16	0.17	0.37	0.40	0.26	0.36
RMSE (mgm^{-3})	0.23	0.27	0.19	0.21	0.53	0.52	0.33	0.43

Table 2. Table of model performance statistics, with data sorted based on whether they were considered to display a significant wind shift due to slope winds or not, and for 06:00 to 10:00 only.

averaging times.

These statistics show that model performance is no different when using hourly averages compared with ten-minute averages ($p<0.05$) for either of the two seasons. It appears from these results that, despite the possible poor representation of the wind direction when using hourly-averaged data, model performance is as good as for model predictions based on ten-minute averaged data.

In order to identify whether model performance is adversely affected on days experiencing these wind shifts relative to other days, the data were sorted into wind shift days and non-wind shift days, and model performance statistics were calculated using data from 06:00 to 10:00, the period around morning rush hour, rather than considering the whole 24-hour period. The results are shown in Table 2. For the 06:00-10:00 period, there is no statistically significant difference between model performance between days showing shifts and those with no significant shifts, nor between ten-minute averaging and hourly averaging ($p<0.05$).

5. Conclusions

A model for the prediction of carbon monoxide concentrations near roads needs to consider site-specific measurements of wind speed and wind direction. In general, higher concentrations are observed when the wind is such that the monitor is leeward of the road compared to windward, as expected. Consideration of the wind direction (whether windward or leeward) at this suburban site is important since the occurrence of slope winds frequently results in wind shifts at peak traffic times. Despite this, model performance is not adversely affected by the choice of archiving data at hourly averages relative to ten-minute averages, providing wind direction is taken into consideration in making the model predictions, even under conditions of significant wind shifts that often coincide with the morning peak traffic flows.

Acknowledgements

The authors wish to thank Environment Waikato for providing the air quality data required for this study and financial assistance for carrying out this work.

References

Eskridge R.E. and S.T. Rao, 1986: Turbulent diffusion behind vehicles: experimentally determined turbulence mixing parameters. *Atmospheric Environment,* 20(5), 851-860.

Gronskei, K.E., 1988: The influence of car speed on dispersion of exhaust gases. *Atmospheric Environment,* 22(2), 273-281.

Hanna, S.R., Briggs G.A., and Hosker, P.H., 1982: *Handbook on Atmospheric Diffusion*, Technical Information Centre, U. S. Department of Energy.

Dirks, K.N., Johns, M.D., Sturman, A.P., and Hay, J.E., 2001: A simple semi-empirical model for predicting missing carbon monoxide concentrations. *Atmospheric Environment*, 36, 5953-5959.

Submitted to Weather and Climate June 2003; *revised December 2004.*