Air quality at higher levels: results from detailed measurements of the vertical pollution profile to 100m in an urban environment.

R.Watkins[†], J.Palmer[‡]

[†] Department of Mechanical Engineering, Brunel University
[‡] Building Performance Assessment Centre, Building Research Establishment Ltd.

Abstract

A knowledge of the pollution concentrations at elevated heights is important as this is often where fresh air inlets are sited for mechanically ventilated buildings. Few detailed data have been published for measurements taken above the first 15-20m in city centres. To provide an insight into the variation of pollution in height and time an experiment has been set up in which the concentration of carbon monoxide has been measured at nine heights up to 100m in the centre of a large city. Data were collected every 10 minutes for more than a year.

The main findings are:

1. Mean long term CO concentrations are low (less than 1ppm), and at 100m about 50% of the ground level ones.
2. The vertical pollution profile is approximately logarithmic (reducing with height), but shows a point of inflection between 20-30m where pollution concentrations were higher than might be expected.
3. Short-term episodes occur when the pollution gradient reverses leading to higher CO concentrations at 100m than lower down. Concentrations reached 10ppm at 100m.
4. Wintertime diurnal profiles show typical traffic-related peaks. Summertime profiles can show the morning pollution peak building and a high level being maintained throughout the day.

The results suggest that at certain times, the "fresh air" drawn into buildings at high level may be significantly polluted, even equal to that at street level. Carbon monoxide was used as a simple indicator of pollution, mostly from traffic. However, it is quite likely that other pollutants NOx, SO_2 and VOCs are also to be found at elevated levels. This may have important implications for occupant health and comfort inside urban buildings.

Introduction

Many people work in urban environments where the air is polluted from a variety of sources. To provide cleaner air for those working inside, the traditional approach has been to seal the façades of buildings and distribute filtered air, with the external “fresh” air usually drawn in at high level. In fact, it is often considered unacceptable to permit natural ventilation of urban office space.

This strategy assumes that pollution emanates predominantly from ground level sources, and is sufficiently diluted at upper levels. However, previous work[1,2], lasting a week in the central area of Birmingham, has shown that in some circumstances an air-conditioned building with air-intake at high level took in more highly polluted air than a naturally ventilated one at low level.

There is considerable interest in encouraging novel approaches to the design of naturally ventilated buildings in urban areas. Given that the pollution concentration of external air has a significant impact on internal air quality, there is a need to understand in greater detail the vertical profile of pollution in the urban canopy layer.

Ajiboye et al[3] have published results of a five day test of the vertical gradient of NO_2 and PM_{10} up to 30m outside an office. The concentrations of NO_2 and PM_{10} were found to change with height but in different ways. NO_2 at 23m was double the concentration at 5m above ground level; beyond this height its concentration reduced. PM_{10} at 11m was about half its value at 5m and remained around this value at higher elevations.

Work by Rubino et al[4] on a 100m occupied building with mechanical ventilation showed a reduction in CO of about 25% from the bottom to the top of the building.

However, there is little substantial long term monitoring in the UK. The present study attempts to provide long-term basic information on the vertical pollution profile and how this varies through time.

Sampling

In order to study the vertical profile of pollution, it is necessary to have a tall support for the measurement equipment which interfers with the air flow as little as possible, and preferably is not itself a source of the measured pollutant.

Permission was granted by British Telecom to make use of their Radio Tower in Birmingham. This building is approximately 150m tall, very narrow, and not itself a direct source of pollution. It is situated in a business area of the city, with an eight lane urban road 100m away, and close to where the previous pollution study took place. This is an ideal monitoring situation.

A suitable harness was constructed to support a total of 0.5km of PVC tubing which was lowered from the 23rd floor into position on the outside of the building. Nine sampling lines collected air from heights of from 7 to 97m above ground level.

The sampling lines were connected to an automatic sampling system which allowed each line to be connected in turn to an electrochemical carbon monoxide analyser. A large purging pump was used to draw air up all lines continuously, with a smaller sampling pump connected to the analyser. One minute settling time was allowed before the CO concentration was measured, which pre-monitoring tests had shown to be adequate. Each measurement cycle lasted ten minutes (9 one minute measurements followed by one minute's delay), generating 144 pollution profiles a day. Data were stored to disk automatically at midnight each day.

The shortest sample tube (23rd floor level) was sampled first to improve simultaneity of measurement. A laptop computer controlled both the operation of the solenoid valves on each sample line, and acted as datalogger.

Carbon monoxide, although not the most important pollutant, was used as an indicator of pollution levels because it is relatively inert, and measurement is unaffected by long sampling lines. The analyser's output is sensitive to temperature and this was logged every ten minutes. The CO data were subsequently normalized to 20ºC. Using a single CO cell ensures that relative differences in concentration are accurately measured, irrespective of absolute accuracy.

Results

Variation with height

Table A shows the average, 24 hour concentration of carbon monoxide for summer and winter periods. Owing to temporary logging problems, data for the full length of the seasons were not available. Data for November and December were used to illustrate winter concentrations, and July and August for summer ones.

HEIGHT, m	MEAN CO, ppm		MAXIMUM CO, ppm (10 minute value)	
	Winter n=7200	Summer n=8064	Winter	Summer
97	0.45	0.52	8.30	3.70
78	0.48	0.57	8.80	6.30
61	0.55	0.61	9.80	4.20
49	0.59	0.65	9.50	3.40
41	0.62	0.68	9.80	3.70
32	0.65	0.68	9.50	3.70
24	0.70	0.75	9.50	3.90
16	0.73	0.77	9.50	7.10
7	0.88	0.95	10.00	4.90

Table A. Mean 24 hour, and maximum values of carbon monoxide.

The profiles of these mean data are shown in Figure A. There is little difference between the summer and winter shapes. A sharp initial fall in concentration up to about 20m is followed by an inflection and a gradually reducing concentration up to 97m. Although the inflection is small, it is a real effect, as the same analyser was used for all sampling points, and the mean profile is an average of many thousands of points.

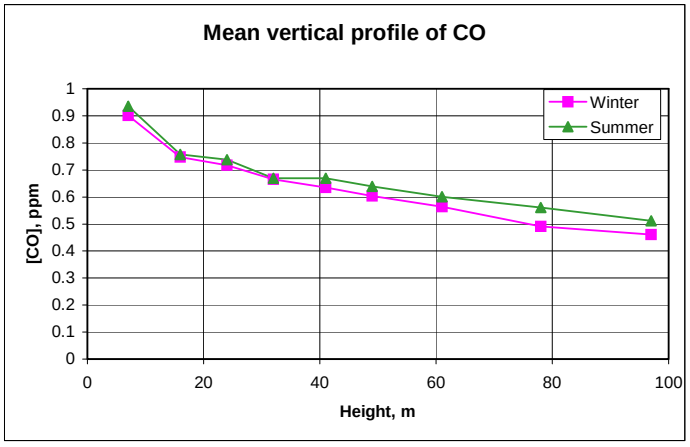

Figure A. Mean 24 hour vertical profiles of carbon monoxide.

Table B and Figure B show the mean profiles of the daily mean values during office hours only (08.00-18.00). All mean values are higher during office hours. Winter values are approximately 42% higher at lower levels (below 25 m) and 35% higher at upper levels. Summer values are about 35% higher at lower levels, but only marginally higher, 6-10%, at higher levels.

Figure B also shows the approximate logarithmic relationship between height and mean concentration.

HEIGHT, m	MEAN CO, ppm		MAXIMUM CO, ppm (10 minute value)	
	Winter n=2138	Summer n=2394	Winter	Summer
97	0.62	0.54	7.27	2.46
78	0.67	0.63	6.76	2.46
61	0.77	0.69	7.48	2.76
49	0.82	0.75	6.96	2.76
41	0.88	0.81	7.27	2.97
32	0.92	0.80	7.27	2.76
24	1.00	0.93	9.01	2.76
16	1.08	0.94	7.48	3.48
7	1.28	1.23	7.78	4.51

Table B. Mean office hours, and maximum values of carbon monoxide.

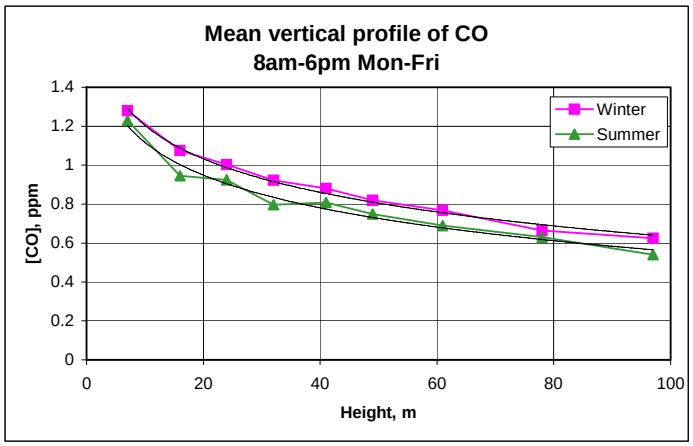

Figure B. Mean office hours vertical profiles of carbon monoxide.
Logarithmic regression lines have been fitted.

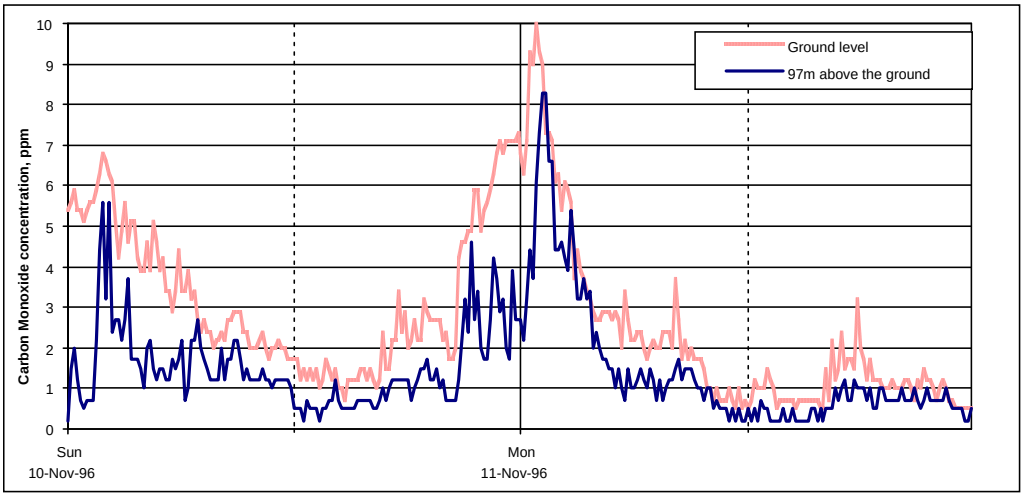

Figure C. Example of high pollution episode where the concentration of CO at high level can equal the ground level concentration.

In certain conditions, particularly when the wind speed is low and a temperature inversion possible, pollutant concentrations at high level (97m) matched those at ground level. For

examples over a period of two days see Figure C. During this period, wind speed, as recorded at Elmdon airport 10km away, was below 1m/s for 80% of the time up until 09.00 hours on Monday morning. Ground level temperature (at Elmdon) fell below 0ºC at night. At 3.00am on Monday morning the vertical profile was reversed in the upper layers, although only temporarily. The point of inflexion at about 25m is again visible. See Figure D.

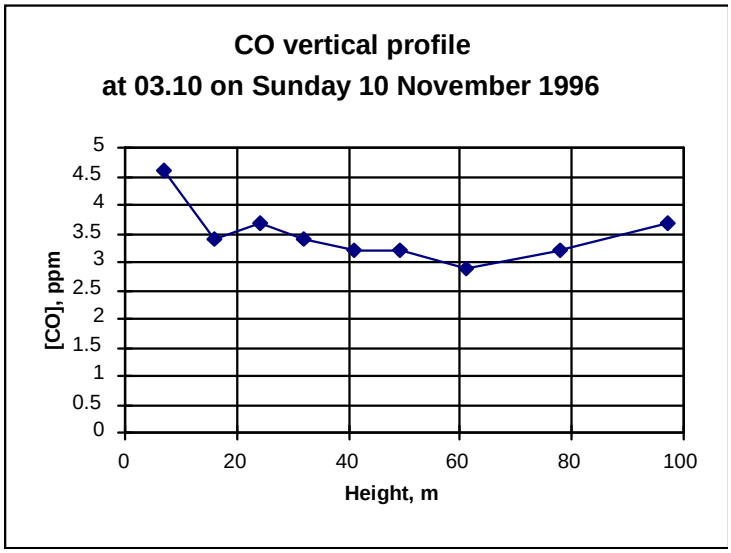

Figure D. Reversal of CO concentration gradient at upper levels.

Variation with time

The daily pattern of the vertical profile is shown in Figures E and F, which depict mean 24 hour profiles for winter and summer months. Each plotted point is the mean of all data measured for that particular time of day; an average of up to 61 values.

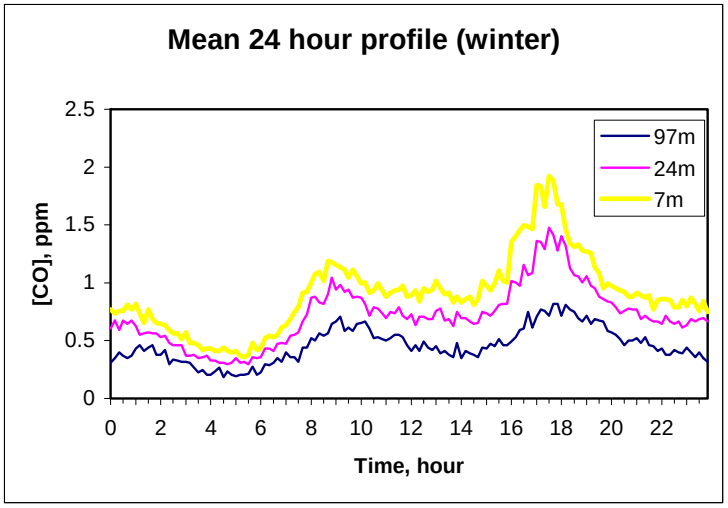

Figure E. The mean variation of CO concentration over 24 hours (winter).

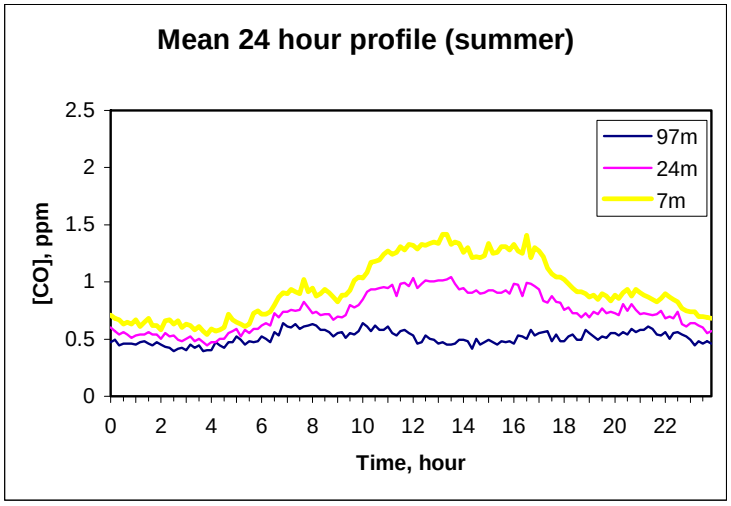

Figure F. The mean variation of CO concentration over 24 hours (summer).

It can be seen that in the winter, between 00.00 and 02.00, CO is decreasing at the 7m and 24m levels, but increasing at 97m. This is not seen in the summer data.

Discussion

The results show that the vertical distribution of carbon monoxide varies considerably through time, and that the maximum value (about 10ppm) may be found at all heights up to 97m. Of particular importance to building occupants is the finding that mean concentrations at 25-30m are only 25-30% lower than those at ground level. The majority of offices in the UK are below or at this height, and obtain ventilation from this air layer.

The mean concentration of CO over 24 hours:
- is low, less than 1ppm.
- reduces with height, in summer or winter.
- at high level (97m) is about half the ground level (7m) concentration, in summer or winter.

There are a number of differences between the winter and summer 24 hour profiles, Figures E and F:
- At 09.00 in the winter, pollution starts to decline at all levels, whereas in the summer this is the point at which pollution starts to increase in concentration.
- In the winter, all three traces track each other up and down through the day. In the summer, this is true up to 10.00, but then the upper level concentration diverges from the low level ones, which continue to track each other. At about 21.00 the 97m trace is back in sync.
- The late afternoon peak (usually associated with traffic) is absent in the summer. In fact from about 16.00 onwards, pollution is declining rather than increasing.

These summer to winter differences are difficult to explain, but an important factor may be the lower wind speeds (20% slower) in the summer. Calmer conditions will lead to a reduced rate of mixing, and increased pollution at lower levels from the traffic on the 8 lane road 100m away. However, the meteorological parameters have not been explored in depth.

The rise in CO at 97m around 01.00 hours in the winter may be due to combustion products from boiler(s) in the area rising from the tops of buildings towards the upper levels. It is interesting to speculate on this since roughly speaking an equal amount of combustion of fossil fuel takes place within the buildings in winter as in the vehicular traffic adjacent to

them. Further studies measuring more appropriate combustion products would be very valuable. Certainly this would explain the absence of this effect in the summer. The occurence of temperature inversions in the winter would also enhance the accumulation of such products at upper levels.

Conclusions

An investigation of the urban vertical profile of CO in a major city has shown that the seasonal concentration at 100m height is about 50% of that at ground level. Long term concentrations are low, 1-2ppm, but high values of 10ppm were observed at all heights. Similarly, CO reduces in concentration logarithmically with height on average, but there is often a point of inflection (higher than expected CO) at about 25m. Moreover, at times, there can be a temporary reversal of the concentration gradient.

The variation with time of the pollution profile outside a building lends support to the idea[3] that there may be benefit in monitoring external conditions, and modulating the degree of external air that is admitted into a building. In this way, the impact of external pollution episodes on indoor air quality can be minimized.

Acknowledgements

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