PERGAMON

Atmospheric Environment 35 (2001) 995–1000

ATMOSPHERIC ENVIRONMENT

www.elsevier.com/locate/atmosenv

An intensive two-week study of an urban CO_2 dome in Phoenix, Arizona, USA

Craig D. Idso[a], Sherwood B. Idso[b,*], Robert C. Balling Jr.[a]

[a]Department of Geography and Office of Climatology, Arizona State University, Tempe, AZ 85287, USA
[b]US Water Conservation Laboratory, 4331 E. Broadway, Phoenix, AZ 85040, USA

Received 23 May 2000; accepted 10 August 2000

Abstract

Atmospheric CO_2 concentrations were measured prior to dawn and in the middle of the afternoon at a height of 2 m above the ground along four transects through the metropolitan area of Phoenix, Arizona on 14 consecutive days in January 2000. The data revealed the existence of a strong but variable *urban CO_2 dome*, which at one time exhibited a peak CO_2 concentration at the center of the city that was 75% greater than that of the surrounding rural area. Mean city-center peak enhancements, however, were considerably lower, averaging 43% on weekdays and 38% on weekends; and averaged over the entire commercial sector of the city, they were lower still, registering 30% on weekdays and 23% on weekends. Over the surrounding residential areas, on the other hand, there are no weekday–weekend differences in boundary-layer CO_2 concentration. Furthermore, because of enhanced vertical mixing during the day, near-surface CO_2 concentrations in the afternoon are typically reduced from what they are prior to sunrise. This situation is additionally perturbed by the prevailing southwest-to-northeast flow of air at that time of day, which lowers afternoon CO_2 concentrations on the southern and western edges of the city still more, as a consequence of the importation of pristine rural air. The southwest-to-northeast flow of air also sometimes totally compensates for the afternoon vertical-mixing-induced loss of CO_2 from areas on the northern and eastern sides of the city, as a consequence of the northeastward advection of CO_2 emanating from the central, southern and western sectors of the city. Hence, although complex, the nature of the urban CO_2 dome of Phoenix, Arizona, is readily understandable in terms of basic meteorological phenomena and their interaction with human activities occurring at the land/air interface. Published by Elsevier Science Ltd.

Keywords: Automobiles; Boundary layer; Carbon dioxide; City climate; Urban environment

1. Introduction

One of the most well-known environmental consequences of urbanization is the *urban heat island* (Goward, 1981; Oke, 1982). Less well known, but possibly just as pervasive, is a phenomenon we have called the *urban CO_2 dome* (Idso et al., 1998), which is a buildup of carbon dioxide over an urban area that results primarily from the localized burning of fossil fuels.

In our first study of this phenomenon, which was conducted in January of 1998, we made one pre-dawn and one mid-afternoon assessment of the air's CO_2 concentration at a height of 2 m above the ground at approximate 1.6-km intervals on four roadway transects through the metropolitan area of Phoenix, Arizona (Idso et al., 1998). The results of that exercise indicated that as the center of the city was approached, the air's CO_2 content rose from a rural background concentration of the order of 370 parts per million (ppm) to a peak value approximately 30% greater in the afternoon and 50% greater in the hours just before dawn.

Since these increases in the CO_2 content of the boundary-layer air over Phoenix were considerably larger than the few enhancements that have been measured over

* Corresponding author. Tel.: + 1-602-379-4356; fax: + 1-602-379-4355.
E-mail address: sidso@uswcl.ars.ag.gov (S.B. Idso).

1352-2310/01/$ - see front matter Published by Elsevier Science Ltd.
PII: S1352-2310(00)00412-X

other cities (Clarke and Faoro, 1966; Berry and Colls, 1990a, b; Reid and Steyn, 1997), we decided to conduct an intensive investigation of Phoenix's urban CO_2 dome to more rigorously determine its strength and stability. This paper reports the results of that study, which consisted of repeating the measurement protocol of Idso et al. (1998) on 14 consecutive days in January of 2000.

2. Experiment

Fig. 1 depicts the four routes through the metropolitan area of Phoenix, Arizona, that we followed in collecting our data. Two of these transects – nos. 1 and 2 – were chosen to pass through the central portion of the city on major interstate highways, where CO_2 concentrations would be expected to be maximal; while the other two transects – nos. 3 and 4 – were designed to weave in and out of the city at various points around its perimeter. This design strategy allowed us to determine the maximum strength of the urban CO_2 dome (from the results of Transects 1 and 2), as well as its geographical shape and extent (from the results of all four transects).

On 14 consecutive days during the same month of the year as our earlier study – January, but this time in the year 2000 – each of the four transects of Fig. 1 was simultaneously traversed by four separate automobile crews, starting at 0500 LST (Local Standard Time) in the morning and at 1400 LST in the afternoon. While traversing each transect, outside air was drawn into each car's portable CO_2 measurement system through a flexible polyethylene airline that exited the front window of the passenger's side of the car and extended to the front of the vehicle, where it was fixed at a height of 2 m above the ground. CO_2 concentrations of the sampled air were measured by Model LI-800 GasHound infrared gas analyzers (LI-COR, Lincoln, NE), which were calibrated with primary CO_2 standards from the Matheson Co. (East Rutherford, NJ) that were maintained at the US Water Conservation Laboratory in Phoenix. The data were stored in CR10X Measurement and Control Modules and viewed in real time on CR10KD Keyboard Displays (Campbell Scientific Inc., Logan, UT).

3. Results

Assuming automobile exhaust and the aerial effluents of commercial activities are the major sources of the urban CO_2 dome – and noting that data from the Arizona Department of Transportation (1999) indicate that Phoenix weekday traffic is nearly 50% greater than weekend traffic – we separated our data into weekday (high vehicular traffic and commercial activity) and weekend (less vehicular traffic and commercial activity) groupings. Fig. 2 thus depicts the results we obtained for the 0500 data acquisition run of Transect 1 on the 10 weekdays and four weekend days of our study, which we present for the purpose of displaying the nature of the

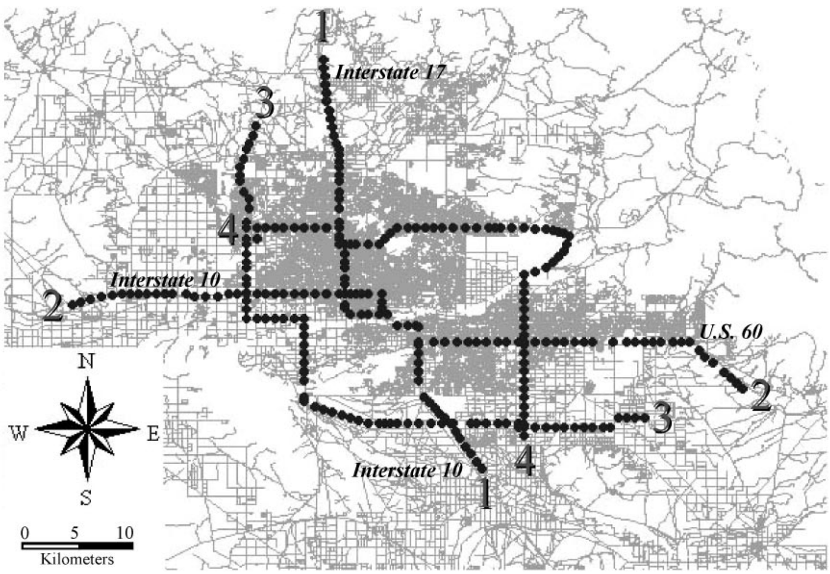

Fig. 1. Street density map of the Phoenix metropolitan area showing the locations of the four transect routes and the points where the CO_2 concentration data were obtained. Solid gray denotes regions where street density is high. Travel across the routes was from southeast to northwest.

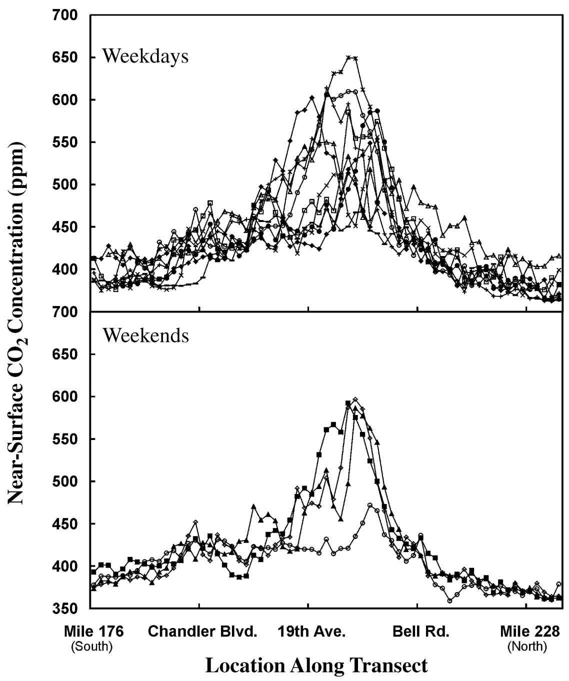

Fig. 2. CO_2 concentration values at each of the measurement locations of the ten weekday and four weekend pre-dawn data acquisition runs of Transect 1. The named locations along the abscissa divide the route into four equal-length segments.

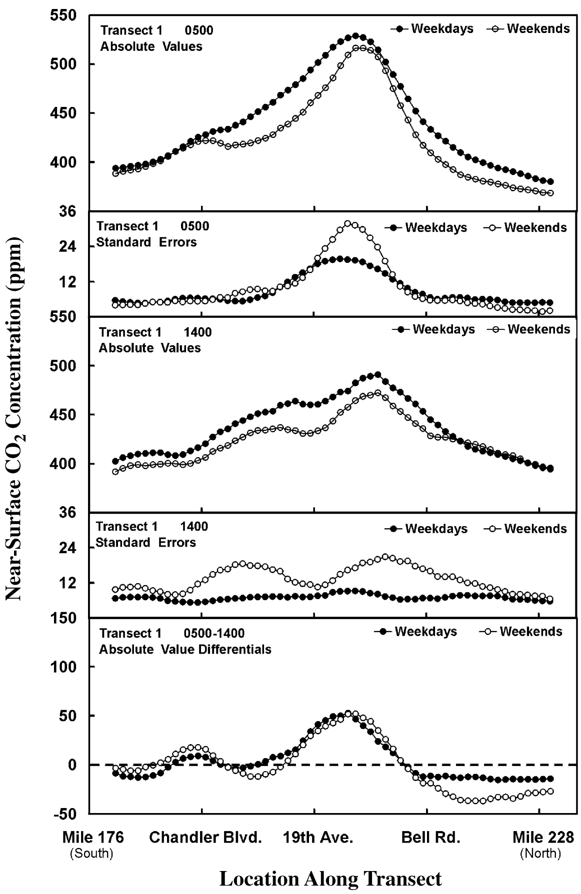

Fig. 3. Seven-term running-average means and standard errors of the means for the pre-dawn and mid-afternoon data acquisition runs of Transect 1. The named locations along the abscissa divide the route into four equal-length segments.

spatial and temporal variability that was typical of the data we obtained.

Figs. 3–6 depict our full set of results in terms of means and standard errors of the means for all four transects for both the pre-dawn and mid-afternoon time periods. The data presented are seven-term running averages of weekday and weekend means. That is, each data point shown was obtained by calculating the mean and standard error of the mean for each individual sampling point on each route and time period for the weekday and weekend data groupings and then, starting at the beginning point of each transect, computing the average of the first seven data points and plotting that result (for both mean and standard error) at the location of the middle or fourth of the seven data point locations, after which the grouping of seven data points was advanced by one location interval and the averaging and plotting procedures repeated.

4. Discussion

The results from the rural portions of our four transects produced mean non-urban CO_2 concentrations of 378.2 ppm for weekdays and 372.7 ppm for weekends. Although the difference between these two results is not statistically significant, it suggests that some of the sites at which these values were obtained may not have been totally outside the influence of the city; for the drop in vehicular traffic and commercial activities between weekdays and weekends reduced the mean CO_2 concentration of the near-surface boundary-layer air there by 5.5 ppm. Hence, the appropriate CO_2 concentration to use in evaluating the strength of the Phoenix urban CO_2 dome in January is probably something less than 372.7 ppm. We have thus used a value of 369.0 ppm for this purpose, because that was the mean weekend value we measured at the northernmost point of Transect 1, which appeared to be the most pristine of our transect end points.

In viewing the results of Figs. 3–6, it can be seen that, during the period of our study, Phoenix's urban CO_2 dome was most pronounced in the central portion of the city in the pre-dawn hours of the morning; and in viewing the raw data of Fig. 2, it can be seen that the CO_2 content

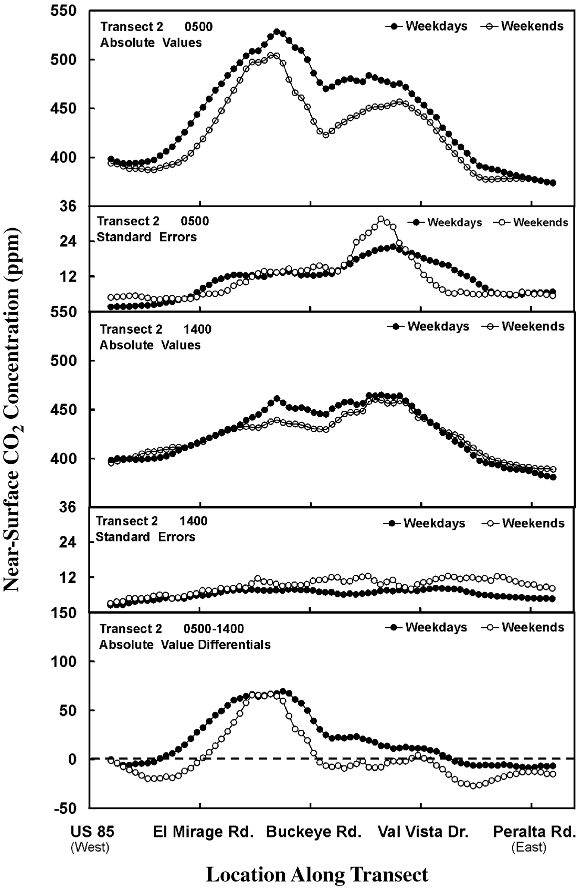

Fig. 4. Seven-term running-average means and standard errors of the means for the pre-dawn and mid-afternoon data acquisition runs of Transect 2. The named locations along the abscissa divide the route into four equal-length segments.

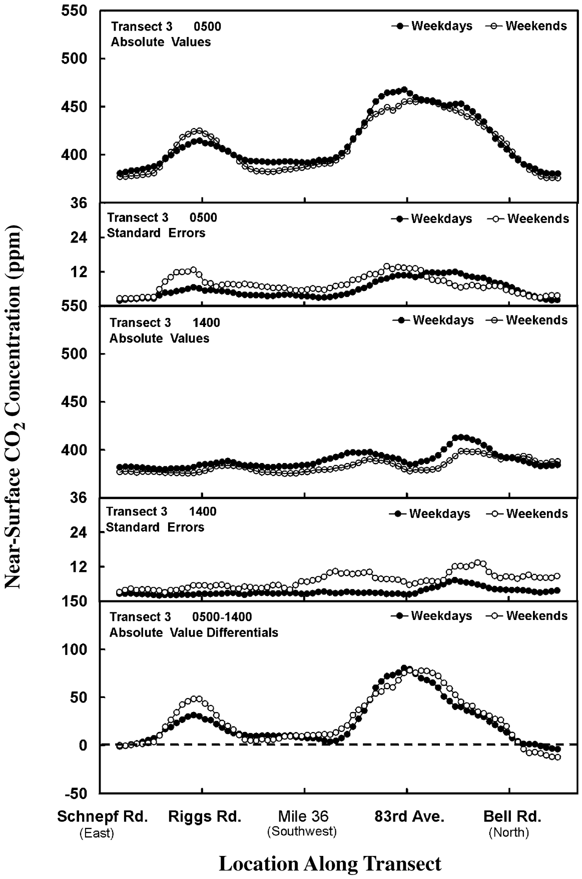

Fig. 5. Seven-term running-average means and standard errors of the means for the pre-dawn and mid-afternoon data acquisition runs of Transect 3. The named locations along the abscissa divide the route into four equal-length segments.

of the near-surface boundary-layer air at that place and time varied significantly from day to day. The highest single weekday peak concentration we measured (on both Transects 1 and 2) was 650 ppm, which is 76% greater than our baseline value of 369 ppm; while the lowest single weekday peak value we measured was 471 ppm, or 28% greater than the rural baseline value.

In terms of peak weekday and weekend *means*, maximum CO_2 concentrations in the center of the city were 528.8 and 510.4 ppm, respectively; and this difference is statistically significant at the 99% confidence level. Hence, average peak city-induced near-surface boundary-layer CO_2 concentration enhancements were 43.3 and 38.3% for weekdays and weekends, respectively, so that the ratio of the average peak weekday enhancement of the air's CO_2 concentration to the average peak weekend enhancement was $43.3\%/38.3\% = 1.13$.

For most of the urban area, however, the ratio of weekday to weekend CO_2 concentration enhancement was significantly greater than that exhibited at the very center of the city. From Chandler Boulevard to Bell Road along Transect 1 (see Fig. 3), for example, the mean city-induced CO_2 concentration enhancement was 29.0% on weekdays and 22.9% on weekends; while from El Mirage Road to Val Vista Drive along Transect 2 (see Fig. 4), it was 31.8 and 23.8% on weekdays and weekends, respectively. Consequently, the ratio of the weekday to weekend city-induced percent CO_2 concentration enhancement over the specified portion of Transect 1 was $29.0\%/22.9\% = 1.266$, while it was $31.8\%/23.8\% = 1.336$ over the specified portion of Transect 2. For the bulk of the urban portion of the city, then, weekday traffic and commercial activities increased pre-dawn near-surface boundary-layer atmospheric CO_2 concentrations about 30% more than did weekend traffic and commercial activities $[(26.6\% + 33.6\%)/2 = 30.1\%]$.

In the more residential suburbs of the metropolitan complex, on the other hand, pre-dawn CO_2 concentrations were nearly identical on weekdays and weekends, as may be seen from the results obtained over basically all of

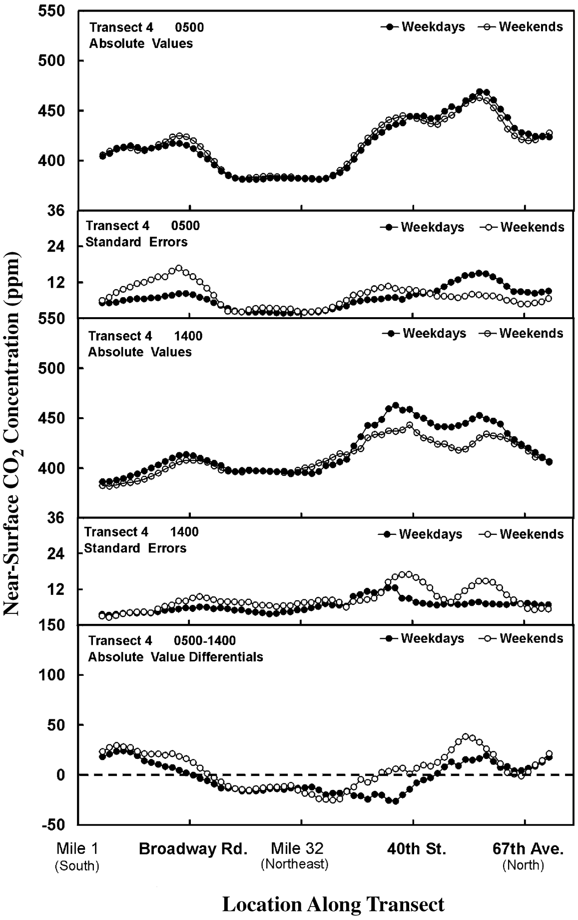

Fig. 6. Seven-term running-average means and standard errors of the means for the pre-dawn and mid-afternoon data acquisition runs of Transect 4. The named locations along the abscissa divide the route into four equal-length segments.

Transects 3 and 4. Hence, the pre-dawn CO_2 consequences of heightened work-week activities in Phoenix were experienced almost exclusively in the more heavily commercialized parts of the city and not in the surrounding residential areas, just as the pre-dawn CO_2 consequences of residential activities were not felt to any significant degree outside the borders of the residential areas, i.e., in the surrounding desert, farmlands and mountains.

The patterns described above for the pre-dawn period were not as well defined in the mid-afternoon, when enhanced vertical mixing reduced the CO_2 concentration in the near-surface boundary-layer air nearly everywhere. In addition, the predominant southwest-to-northeast airflow at that time of day (Hunt et al., 2000) brought with it more pristine air from the uninhabited regions to the south and west of the Phoenix metropolitan area. This phenomenon further reduced CO_2 concentrations on the southern and western sides of the city at the same time that it transported CO_2 from the southwest to the northeast, replenishing some of the CO_2 that was moved up and out of the northern and eastern parts of the city.

This phenomenon is particularly evident in the data of Transect 2, which runs predominantly east–west along its entire length. In the pre-dawn hours of both weekdays and weekends, the greatest CO_2 concentrations occurred in the western portion of the metropolitan area; but by mid-afternoon – when the mean wind on the days of our study was out of the WSW ($240 \pm 20°$) – the western peak was much reduced but the eastern peak was nearly as great as it was in the early morning, which resulted in the eastern peak actually being slightly greater than the western peak at that time of day. Likewise, the two urban areas that are traversed by Transect 3 have little built-up areas to either the south or west of them, so that in the afternoon, their mini-CO_2 domes were essentially swept away by the combined action of vertical mixing and the prevailing surface airflow from the southwest. Transect 4, on the other hand, initially runs north on the eastern edge of a sizeable urban sector and then, after momentarily leaving the high-density inhabited area of the city, turns west through an even more extensive urban area, so that both of its mini-CO_2 domes were preserved in the afternoon by the advection of city-produced CO_2 from the south and west, while the CO_2 concentration of the less-inhabited area between them was actually slightly increased. Finally, on Transect 1, the peak CO_2 concentration shifted a little further north in the afternoon; and the air at its northernmost end, which was largely unaffected by urban air prior to dawn, clearly was impacted by city-produced CO_2 in the afternoon, much like that of the non-urban middle section of Transect 4.

5. Conclusions

The cluster of cities that comprises the metropolitan area of Phoenix, Arizona, produces a sizeable increase in the CO_2 concentration of the near-surface boundary-layer air that overlies it. At the very center of the urban complex, concentrations are highly variable and can be quite large. In this winter study of 14 days' duration, for example, peak city-center CO_2 concentrations measured in the hours just before dawn ranged from 28 to 76% higher than what was typical of the surrounding desert, farmland and mountains; while the mean enhancement of the background CO_2 concentration at the city center was 43.3% for weekdays and 38.3% for weekends.

Over the extended portion of the city that includes its major commercial developments, this weekday–weekend dichotomy was even more pronounced, with urban CO_2 enhancements averaging 30.4% on weekdays and 23.4%

on weekends. The ratio of these two numbers (30.4/23.4 = 1.30) indicates that work-week activities within the high-commerce sector of the city boosted CO_2 concentrations there by fully 30% above what they were on non-workdays. Over the primarily residential areas of the city, on the other hand, there were no significant differences between work-week and weekend CO_2 concentrations.

Due to enhanced vertical mixing during the day, mid-afternoon near-surface CO_2 concentrations over the city were generally reduced from what they were in the hours prior to sunrise. This pattern was modified and made more complex, however, by the afternoon airflow from the southwest to the northeast. This phenomenon resulted in areas on the southern and western sides of the Phoenix metro area having their CO_2 concentrations reduced even more during the day, as pristine air from the outlying rural areas mixed with, and displaced, the local boundary-layer air that carried the CO_2 signature of the city. Areas to the north and east, on the other hand, tended to have their CO_2 concentrations augmented, sometimes to such a degree that the loss of CO_2 due to vertical mixing there was totally compensated by advected CO_2 from the south and west.

These findings may be of relevance to international discussions related to the ongoing rise in the air's CO_2 concentration and its implications for the future, as many of the world's major cities may already be covered by urban CO_2 domes with carbon dioxide concentrations equivalent to what is being predicted for a 100 years from now. It is thus possible that these cities could serve as "natural laboratories" for investigating certain of the pressing questions that currently vex policy makers, especially since these cities also tend to exhibit significant heat island effects. With elevated temperatures and CO_2 concentrations relative to surrounding rural areas, large metropolitan complexes may be valuable analogues of both global warming and atmospheric CO_2 enrichment.

Acknowledgements

Funding for this research was provided by the National Science Foundation (#UPAS8/11/99). Other support was provided by the Agricultural Research Service, US Department of Agriculture, and the Carbon Dioxide Research Program of the Environmental Sciences Division, US Department of Energy, under Interagency Agreement DE-AI02-93ER-61720.

References

Arizona Department of Transportation, Transportation Planning Division, 1999. Daily and seasonal adjustment factors by seasonal factor group: 1998 traffic year.

Berry, R.D., Colls, J.J., 1990a. Atmospheric carbon dioxide and sulphur dioxide on an urban/rural transect – I. Continuous measurements at the transect ends. Atmospheric Environment 24A, 2681–2688.

Berry, R.D., Colls, J.J., 1990b. Atmospheric carbon dioxide and sulphur dioxide on an urban/rural transect – II. Measurements along the transect. Atmospheric Environment 24A, 2689–2694.

Clarke, J.F., Faoro, R.B., 1966. An evaluation of CO_2 measurements as an indicator of air pollution. Journal of the Air Pollution Control Association 16, 212–218.

Goward, S.N., 1981. Thermal behavior of urban landscapes and the urban heat island. Physical Geography 2, 19–33.

Hunt, J.C.R., Fernando, H.J.S., Grachev, A.A., Pardyjak, E.P., Berman, N.S., Anderson, J., 2000. Slope-breezes and weak air movements in a wide enclosed valley. Journal of the Atmospheric Sciences, submitted for publication.

Idso, C.D., Idso, S.B., Balling Jr., R.C., 1998. The urban CO_2 dome of Phoenix, Arizona. Physical Geography 19, 95–108.

Oke, T.R., 1982. The energetic basis of the urban heat island. Quarterly Journal of the Royal Meteorological Society 108, 1–24.

Reid, K.H., Steyn, D.G., 1997. Diurnal variations of boundary-layer carbon dioxide in a coastal city – observations and comparison with model results. Atmospheric Environment 31, 3104–3114.