Does the urban CO₂ dome of Phoenix, Arizona contribute to its heat island?

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Abstract. Phoenix, Arizona has both a strong urban heat island and a large near-surface atmospheric CO₂ “dome” during periods of atmospheric stability. In this investigation, we use a detailed one-dimensional infrared radiation simulation model to determine the thermal impact of the elevated CO₂ levels in the urban environment. We find that the increased CO₂ concentrations below the inversion layer contribute only slightly to the observed heat island, which suggests that other factors, such as absorption of solar energy by urban surface materials and lower soil moisture levels, are largely responsible for the observed increase in urban temperatures.

1. Introduction

Over the past several years, the atmospheric carbon dioxide (CO₂) “dome” over the growing Phoenix, Arizona metropolitan area has been the focus of an intense multidisciplinary study. The combination of large emissions of CO₂ throughout a city highly dependent on private passenger vehicles (over 100 million vehicle-km per day), a relatively stable atmosphere in a desert climate, the valley setting of a city surrounded by mountains, and a relatively sparse vegetative cover produces atmospheric CO₂ levels in the center of the city that routinely exceed 550 parts per million by volume (ppmv), as opposed to approximately 380 ppmv outside the city [Idso et al., 1998, 2001; Martin and Stabler, 2000]. This large increase in urban CO₂ levels dwarfs the 5 to 10 ppmv urban increases reported to date in the literature for other cities, such as Cincinnati [Clarke and Faoro, 1966], Nottingham [Berry and Collins, 1990], and Vancouver [Reid and Steyn, 1997].

A series of experiments is underway to determine the role of local meteorology and human activities on the shape and intensity of the urban CO₂ dome in Phoenix. Measurements of atmospheric CO₂ (taken with Model LI-800 GasHound CO₂ Gas Analyzers) have been made (a) dozens of times along freeway transects (Figure 1) throughout the city [Idso et al., 2001; Wentz et al., 2001], (b) at stationary locations for which one-minute resolution data are available [Idso et al., 2002], and (c) from single-engine airplane transects flown at various heights. These datasets show that CO₂ levels are greatest during winter evening and morning periods when the atmosphere is most stable and vehicular traffic is increased substantially by winter visitors [Idso et al., 1998, 2001, 2002; Wentz et al., 2001]. Spatial variations in the CO₂ dome appear to be most strongly related to the level of urbanization; vegetation appears to slightly modulate the spatial pattern, particularly in the high-sun months, by absorbing CO₂ via photosynthesis during the day and releasing CO₂ via respiration at night [Wentz et al., 2001].

Satellite-based and thermometer-based temperature maps of the Phoenix area show a particularly well-developed urban heat island during the nighttime and early morning hours [Hsu, 1984; Balling and Brazel, 1988; Stoll and Brazel, 1992; Brazel et al., 2000]. Near-surface air temperatures in the urban core are frequently 5°C to 10°C warmer than temperatures in the surrounding area during periods when the atmosphere is most stable. The heat island is best developed when winds are light in the absence of significant synoptic activity. The same basic time and space relationships hold true of the urban CO₂ dome—the highest CO₂ values occur in the urban core, and the CO₂ dome is best developed when the atmosphere is stable and winds are light. Despite their apparent strong association in both time and space, and despite the enormous literature linking elevated atmospheric CO₂ concentrations to a rise in temperatures, it is not clear that the urban heat island is caused by the CO₂-induced thermal forcing of the urban CO₂ dome. In this investigation, we conduct a series of numerical simulation experiments to determine the degree to which the elevated CO₂ in the urban area contributes to the observed increase in temperature in downtown Phoenix.

2. Model and Inputs

Extensive measurements of the Phoenix CO₂ dome were made over a 14-day period in January 2000 including twice-daily freeway transect data and once-daily aircraft transect data. The synoptic situation of the entire period was nearly identical from day to day with high pressure dominating the entire southwestern United States, a weak circulation on a regional scale, clear skies, and a strong atmospheric inversion in the morning hours. Near-surface measurements revealed atmospheric CO₂ levels near 380 ppmv in the outlying areas and 550-600 ppmv in downtown areas. Measurements made from the airplane showed that the elevated CO₂ levels decline rapidly to the height of the morning

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Figure 1. Map of Phoenix, Arizona showing freeway transects used to collect CO₂ data.
inversion layer (typically 300-500 m above the ground) and are near 380 ppmv above that level (Figure 2). Although surface CO₂ levels in downtown Phoenix were several hundred ppmv higher than those of outlying areas, vertical integration of the entire column reveals that the total CO₂ content was only a few ppmv higher in the downtown area. Nonetheless, the shallow CO₂ blanket in the city could contribute to the higher temperatures of the urban heat island.

To study that potential contribution, we selected a detailed one-dimensional infrared radiation simulation model of Chou and Suarez [1994] to determine the thermal impact of the elevated CO₂ levels of Phoenix’s urban CO₂ dome. The model computes infrared fluxes due to water vapor, CO₂, O₃, various trace gases (N₂O, CH₄, CFC-11, CFC-12, CFC-22) as well as clouds and aerosols. The model divides the infrared spectrum into nine bands ranging from 0.53 - 3.33 μm to 29.4 - ∞ μm. An additional narrow band near 15 μm is included to compute flux responses due to N₂O. The model contains 92 layers from the surface to the top of the atmosphere, is initialized using United States Standard Atmosphere profiles, and for our purposes is run with cloud-free conditions. The model has been used successfully by others in replicating high-resolution data from the Earth Radiation Budget Experiment [Ho et al., 1998].

Three different simulations were conducted for this experiment. The first simulation had atmospheric CO₂ concentration maintained at 380 ppmv at all levels (the background level away from the Phoenix metropolitan area), the second had CO₂ concentration doubled at all levels, and the third had CO₂ concentrations that resembled the average profile measured in the Phoenix area (Figure 2).

3. Results

The first simulation with CO₂ maintained at 380 ppmv provided a set of outputs to be compared to the simulations with elevated CO₂. When compared to the control simulation, we find that a doubling of atmospheric CO₂ through the entire atmosphere produces a near-surface temperature increase of 0.46°C above the control run value. While this may seem low compared to 2 x CO₂ global warming estimates of three-dimensional general circulation models [Houghton et al., 1996], our simulations with the Chou et al. model do not include water vapor feedbacks that typically elevate the global temperature response to increased CO₂. Furthermore, there is no evidence that atmospheric moisture levels in Phoenix have increased as the temperatures have risen [Brael and Balling, 1986].

The shallow CO₂ dome situation over the Phoenix metropolitan area, as represented in Figure 2, creates a 0.12°C warming at the surface. When compared to a heat island that is often 5°-10°C warmer than surrounding areas, the model results suggest that factors other than elevated CO₂ are largely responsible for maintaining higher temperatures in downtown Phoenix.

The reason the urban CO₂ dome does not create a more pronounced temperature increase at the surface relates to the differences in infrared (IR) flux throughout the lower atmosphere between simulations (Figure 3). All simulations demonstrate a net upward IR flux, but the 2 x CO₂ simulation has a smaller net upward flux than either the control or urban CO₂ dome simulations. In fact, the greatest warming in the 2 x CO₂ simulation takes place near 775 hPa and not at the surface. General circulation models also show greatest warming in this part of the atmosphere given global increases in greenhouse gas concentrations [Houghton et al., 1996]. This suggests for the 2 x CO₂ simulation that a greater amount of IR radiation is being absorbed through the atmosphere than what is being emitted; the entire troposphere therefore warms substantially.

In contrast, the urban simulation outgoing longwave radiation (OLR) vertical profile matches that of the control simulation through most of the atmosphere. The only difference is that the urban OLR profile has a small "bubble" of less upward flux near the surface, which indicates that the atmosphere below the inversion layer is absorbing more IR than it is in the control simulation. Reductions from the control simulation of up to 0.02 W m⁻² in the lower troposphere are evident in the urban CO₂ simulation, while corresponding increases in IR loss of up to 0.13 W m⁻² take place in the 2 x CO₂ simulation.

The OLR changes discussed above can be translated into temperature variations by examining the differences in the cooling rates of each layer (in °C day⁻¹) of the two model runs from those of the control simulation (Figure 4). At the top of the clear-sky control simulation’s atmosphere, the cooling rate of 7.68°C day⁻¹ is high; the average for the whole atmosphere for the control simulation is 3.54°C day⁻¹. For the 2 x CO₂ simulation, the cooling rate is about 3°C day⁻¹ more than that of

![Figure 2](image-url)  
**Figure 2.** Vertical average CO₂ concentration in Phoenix in the morning during January, 2000.

![Figure 3](image-url)  
**Figure 3.** Differences from control run in OLR for Phoenix (open circles) and doubled CO₂ throughout the atmosphere (open diamonds).
the control at the top of the atmosphere and about 0.7°C day⁻¹ more than that of the control for the average of the whole atmospheric column. The most pronounced increase in the cooling rate is found in the stratosphere and above; below the stratosphere (below 300 hPa), the cooling rate of the 2 × CO₂ simulation is less than that of the control simulation. Since cooling rate is defined by the difference in the OLR between pressure levels, this suggests that although the lower atmosphere would warm (as seen in the OLR), the cooling rate is less because the absorption of IR flux due to CO₂ is greater near the top of the troposphere than at the bottom. Hence, the vertical gradients in IR flux (i.e., the cooling rates) are smaller.

The urban simulation also shows an average higher cooling rate than does the control simulation, but only by a fraction of a degree (an average increase of 0.003°C day⁻¹). The only major difference between the control and urban simulations is that the urban simulation has a region of higher cooling rates at, and below, the inversion layer, due to the small warming in that layer of higher atmospheric CO₂ concentration. The thermal and radiative impacts of the urban CO₂ dome are small, but greater above the surface than at the surface.

4. Conclusions

Past research has demonstrated that the existence of a pronounced urban heat island effect for the Phoenix metropolitan area, as well as an equally pronounced urban atmospheric CO₂ dome across the city. Generally, the higher temperatures coincide in time and space with higher values of atmospheric CO₂; given the literature linking higher temperatures to higher levels of CO₂, it is tempting to declare a strong causal relationship between these two parameters, given the situation in Phoenix.

To better understand the physical linkage between the higher temperatures and higher CO₂ concentrations, we use a 92-layer nine-band terrestrial radiative flux model to simulate the effects of an urban CO₂ dome on atmospheric and surface heating. The results indicate that the effect of the CO₂ dome on Phoenix metropolitan area temperatures is minimal, resulting in surface temperatures that exceed the control simulation by only 0.12°C.

We conclude that the majority of the surface heating associated with the urban heat island effect is due to forcing by phenomena other than the urban CO₂ dome. We suggest that the absorption of solar energy by urban surface materials and lower soil moisture levels in the urban core would be likely factors in explaining most of the observed surface heating.

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