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Does the urban CO_2 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 CO_2 "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 CO_2 levels in the urban environment. We find that the increased CO_2 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 (CO_2) "dome" over the growing Phoenix, Arizona metropolitan area has been the focus of an intense multidisciplinary study. The combination of large emissions of CO_2 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 CO_2 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 CO_2 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 Colls,* 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 CO_2 dome in Phoenix. Measurements of atmospheric CO_2 (taken with Model LI-800 GasHound CO_2 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 CO_2 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 CO_2 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 CO_2 via photosynthesis during the day and releasing CO_2 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 CO_2 dome--the highest CO_2 values occur in the urban core, and the CO_2 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 CO_2 concentrations to a rise in temperatures, it is not clear that the urban heat island is caused by the CO_2-induced thermal forcing of the urban CO_2 dome. In this investigation, we conduct a series of numerical simulation experiments to determine the degree to which the elevated CO_2 in the urban area contributes to the observed increase in temperature in downtown Phoenix.

2. Model and Inputs

Extensive measurements of the Phoenix CO_2 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 CO_2 levels near 380 ppmv in the outlying areas and 550-600 ppmv in downtown areas. Measurements made from the airplane showed that the elevated CO_2 levels decline rapidly to the height of the morning

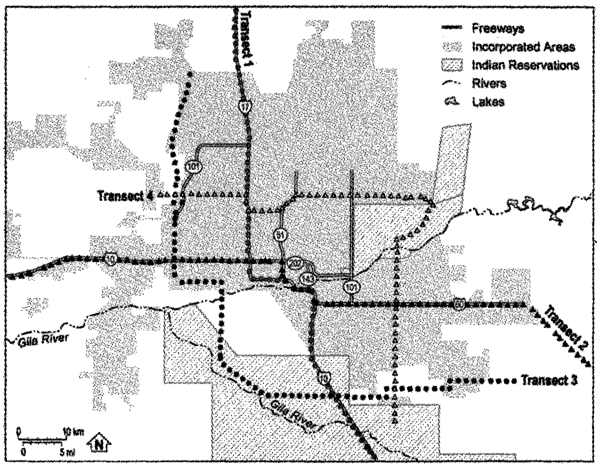

Figure 1. Map of Phoenix, Arizona showing freeway transects used to collect CO_2 data.

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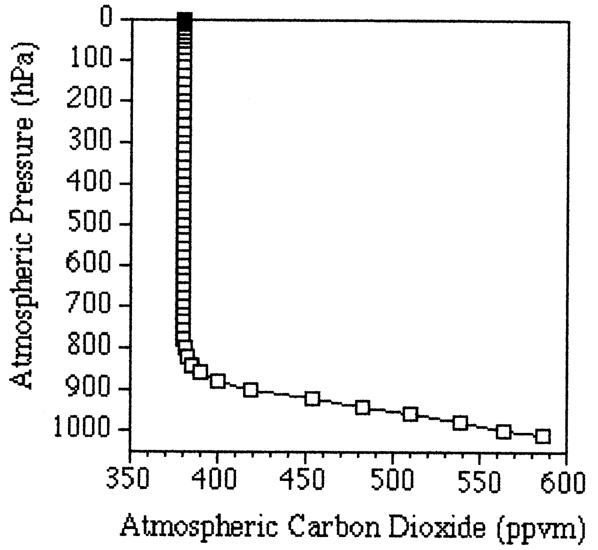

Figure 2. Vertical average CO_2 concentration in Phoenix in the morning during January, 2000.

inversion layer (typically 300-500 m above the ground) and are near 380 ppmv above that level (Figure 2). Although surface CO_2 levels in downtown Phoenix were several hundred ppmv higher than those of outlying areas, vertical integration of the entire column reveals that the total CO_2 content was only a few ppmv higher in the downtown area. Nonetheless, the shallow CO_2 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 Suzrez* [1994] to determine the thermal impact of the elevated CO_2 levels of Phoenix's urban CO_2 dome. The model computes infrared fluxes due to water vapor, CO_2, O_3, various trace gases (N_2O, CH_4, 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 N_2O. 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 CO_2 concentration maintained at 380 ppmv at all levels (the background level away from the Phoenix metropolitan area), the second had CO_2 concentration doubled at all levels, and the third had CO_2 concentrations that resembled the average profile measured in the Phoenix area (Figure 2).

3. Results

The first simulation with CO_2 maintained at 380 ppm provided a set of outputs to be compared to the simulations with elevated CO_2. When compared to the control simulation, we find that a doubling of atmospheric CO_2 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 × CO_2 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 CO_2. Furthermore, there is no evidence that atmospheric moisture levels in Phoenix have increased as the temperatures have risen [*Brazel and Balling*, 1986].

The shallow CO_2 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 CO_2 are largely responsible for maintaining higher temperatures in downtown Phoenix.

The reason the urban CO_2 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 × CO_2 simulation has a smaller net upward flux than either the control or urban CO_2 dome simulations. In fact, the greatest warming in the 2 × CO_2 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 × CO_2 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 Wm^{-2} in the lower troposphere are evident in the urban CO_2 simulation, while corresponding increases in IR loss of up to 0.13 Wm^{-2} take place in the 2 × CO_2 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 × CO_2 simulation, the cooling rate is about 3°C day^{-1} more than that of

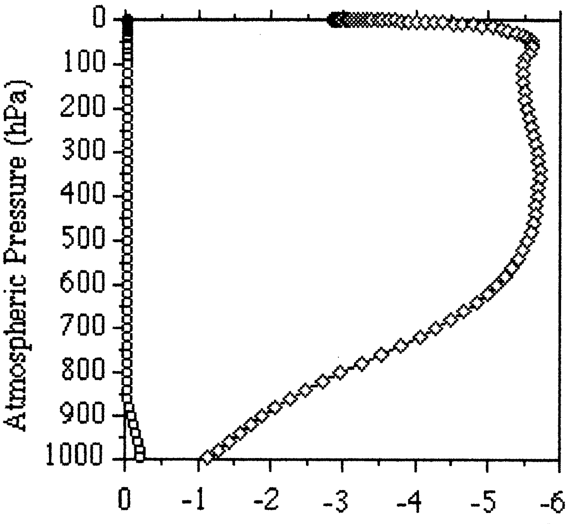

Figure 3. Differences from control run in OLR for Phoenix (open circles) and doubled CO_2 throughout the atmosphere (open diamonds).

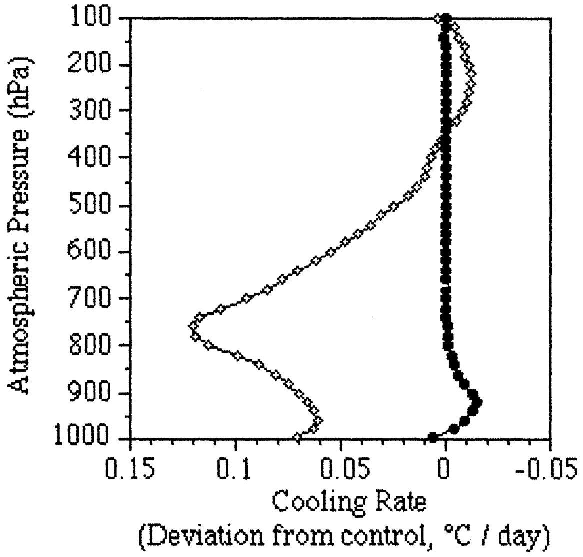

Figure 4. Vertical infrared cooling rate differences from control run for Phoenix (closed circles) and for doubled CO_2 throughout the atmosphere (open circles).

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 $2 \times CO_2$ 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 CO_2 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 CO_2 concentration. The thermal and radiative impacts of the urban CO_2 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 CO_2 dome across the city. Generally, the higher temperatures coincide in time and space with higher values of atmospheric CO_2; given the literature linking higher temperatures to higher levels of CO_2, 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 CO_2 concentrations, we use a 92-layer nine-band terrestrial radiative flux model to simulate the effects of an urban CO_2 dome on atmospheric and surface heating. The results indicate that the effect of the CO_2 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 CO_2 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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