On the causal link between carbon dioxide and air pollution mortality

Mark Z. Jacobson

Received 22 June 2007; revised 14 December 2007; accepted 3 January 2007; published 12 February 2008.

1. Introduction

[2] Because carbon dioxide’s (CO$_2$’s) ambient mixing ratios are too low to affect human respiration directly, CO$_2$ has not been considered a classic air pollutant. Its effects on temperatures, though, affect meteorology, and both feed back to air pollution. Several studies have modeled the sensitivity of ozone to temperature [Stillman and Samson, 1995; Zhang et al., 1998] and the regional or global effects of climate change from all greenhouse gases on ozone [Thompson et al., 1989; Evans et al., 1998; Dvortsov and Solomon, 2001; Mickley et al., 2004; Stevenson et al., 2005; Brasseur et al., 2006; Murzaki and Hess, 2006; Steiner et al., 2006; Racherla and Adams, 2006] and aerosol particles [Aw and Kleeman, 2003; Liao et al., 2006; Unger et al., 2006]. Some studies have highlighted the effect of water vapor on chemistry [Evans et al., 1998; Dvortsov and Solomon, 2001; Stevenson et al., 2005; Steiner et al., 2006; Racherla and Adams, 2006; Aw and Kleeman, 2003]. However, none has isolated the effect of CO$_2$ alone on ozone, particles, or carcinogens, applied population and health data to the pollution changes, or examined the problem with a global-regional climate/air pollution model.

[3] Here, a box photochemistry calculation is first used to show how increases in water vapor and temperature independently increase ozone more with high than low ozone. This analysis helps to explain the causal link between CO$_2$ and health in areas where most people live, as subsequently found in 3-D global-regional simulations.

2. Chemical Effects of CO$_2$ on Ozone

[4] The SMVGEAR II chemical solver was used first in box mode, without dilution or entrainment, to solve chemistry for 12 hours among 128 gases and 395 inorganic, organic, sulfur, chlorine, and bromine reactions (including 57 photoprocesses) (mostly given by Jacobson et al. [2007], also see the supplementary material of Jacobson [2007]). Cases with different initial NO$_x$ and organic gas were run.

[5] Figure 1 shows the water-vapor (H$_2$O) and temperature-dependence of ozone under several ozone precursor combinations. For initial NO$_x$ < 8 ppbv, ozone decreased with increasing H$_2$O. For initial NO$_x$ > 80 ppbv and moderate initial NO$_x$ with low organics, though, ozone increased with increasing H$_2$O, by up to 2.8 ppbv-O$_3$ per 1 ppbv-H$_2$O. Between these extremes, ozone increased with increasing H$_2$O at low H$_2$O and stayed constant or slightly decreased at high H$_2$O (see the auxiliary material).

Figure 1 also shows that, generally (but not always), increasing water vapor increased ozone more with higher ozone.

[6] Further, the more ozone present, the more temperature-dependent chemistry increases ozone (Figure 1), consistent with Stillman and Samson [1995] and Zhang et al. [1998]. The ozone increase (Δχ, ppbv) per 1 K change in temperature (ΔT) from all points in Figure 1 were fit to

$$\frac{\Delta \chi}{\Delta T} = -0.13034 - 0.0045585 \chi + 0.00028643 \chi^2 - 4.6893 \times 10^{-7} \chi^3$$

(1)

where χ is ozone (ppbv) at 298.15 K (32–250 ppbv). A 1 K rise increased ozone by about 0.1 ppbv at 40 ppbv but 6.7 ppbv at 200 ppbv. Olzyna et al. [1997] reported an observed correlation in the rural southeast U.S. of 2.4 ppbv ozone per 1 K. If temperature-dependent chemistry alone was causing this increase, ozone would need to be about 115 ppbv (equation 1) in that study, but it was 30–90 ppbv. Thus, other factors not accounted for in Equation 1, such as H$_2$O increases (described above) and biogenic gas emission increases [e.g., Guenther et al., 1995], due to higher temperatures, may have caused the larger observed temperature-ozone correlation. Also, both temperature and ozone increase with sunlight, so all observed temperature-ozone correlations overestimate the magnitude of cause and effect.

---

1. Department of Civil and Environmental Engineering, Stanford University, Stanford, California, USA.

3. Health Effects of CO₂ From Global-U.S. Simulations

The chemistry used for Figure 1 was applied with emission, aerosol, cloud, meteorological, radiative, transport, and surface-processes in the 3D model, GATOR-GCMOM. The model (see auxiliary material) has been evaluated against U.S. gas, aerosol, meteorological, and radiative data extensively [e.g., Jacobson, 2001; Jacobson et al., 2004, 2007; Colella et al., 2005].

Two global simulations (4°-SN × 5°-WE) were run under present-day conditions. In the second, fossil-fuel CO₂ (fCO₂) ambient mixing ratios and emissions were set to preindustrial values. When U.S. temperatures were about 1 K higher in the present minus preindustrial-CO₂ global simulations, the U.S. regional domain (0.5°-SN × 0.75°-WE) in each global simulation was turned on and initialized with global-domain data (including ambient CO₂). Global and regional domains were run another four months. Emissions of fCO₂ were included in the present-day but not preindustrial-CO₂ global- and U.S.-domain simulations.

Figures 2 and S3 show differences between the present-day and preindustrial-CO₂ simulations. Figure 2a compares modeled with radiosonde (1958–2006) vertical temperature differences. The population-weighted near-surface temperature increase over land was 1.07 K (Table S4), which increased population-weighted H₂O by 1.28 ppbv (Table S4) and U.S.-averaged H₂O by 1.1 ppbv (Figure 2b). The observed 1961–1995 U.S. water vapor increase and positive correlation between temperature and H₂O [Gaffen and Ross, 1999] support the modeled H₂O increase with increasing temperatures.

Figure 2c indicates that fCO₂ increased ozone by 0.12 ppbv in the U.S., 5 ppbv in Los Angeles, 1–5 ppbv in the southeast, and up to 2 ppbv along the northeast coast. In Los Angeles, the 0.75 K temperature increase (Figure 2a) and 1.3 ppbv water vapor increase increased ozone through chemistry (Figure 1).

[11] In the southeast, 0.5–1 K temperature increases increased isoprene and monoterpenes (Figure S3a), reducing the relative humidity (Figure S3c) and cloud optical depth (Figure S3d), increasing ultraviolet radiation (Figure S3e), and enhancing ozone. The 0.5–2 ppbv/K ozone increase in Tennessee is just below the correlated estimate of 2.4 ppbv/K from Olszyna et al. [1997] as expected (section 2). Averaged over the U.S. domain, higher temperatures from fCO₂ increased biogenic soil NO₃, isoprene, monoterpenes, and other organic carbon emissions by 6% (0.01 Tg/yr), 9% (0.47), 9.8% (0.15), and 8.9% (0.14), respectively. In the northeast, higher ozone due to higher temperatures was offset partly by higher cloud optical depth (Figure S3d) and lower ultraviolet radiation (Figure S3e), modestly increasing ozone.

[12] The population-weighted 8-hr ozone increase due to fCO₂ was +0.72 ppbv (Table 1), suggesting a greater increase over populated than less-populated areas. FCO₂ increased particles in populated areas (Tables 1 and S4) by warming the air more than the ground, increasing stability (as with radiosonde data—Figure 2a, ii), decreasing turbulence, shearing stress, and surface wind speed (Table S4 and Figure S3), reducing dispersion. Reduced dispersion and wind speed are consistent with Mickley et al. [2004] who correlated warmer temperatures with reduced cyclone activity. FCO₂ also increased isoprene and monoterpenes emissions, thus secondary organic matter (SOM) (Table S4, Figures S3a and S3b); and increased relative humidity (Table S4) by increasing H₂O, swelling aerosol particles, increasing nitric acid and ammonia dissolution and the surface area for sulfuric acid and organic condensation. FCO₂ increased land precipitation, consistent in direction with observed trends [Intergovernmental Panel on Climate Change, 2001], increasing aerosol removal, but less than other processes increased aerosol concentrations.

[13] Health effect changes (Δy) due to ozone and PM₂.₅ changes in each model cell were determined from [e.g., Ostro et al., 2006],

\[ \Delta y = (1 - \exp(-\beta \Delta x)) y_0 P \]  

where \( \Delta x \) is the simulation-averaged mixing ratio or concentration change in the cell, \( \beta \) is the fractional increase in risk per unit \( \Delta x \), \( y_0 \) is the baseline health effect rate, and \( P \) is the cell population exposed to at least a minimum threshold. Table 1 and its footnote provide values of \( \Delta x, \beta, y_0 \), and thresholds. Changes were summed over all cells and adjusted from a four-month to an annual average (Table 1, footnote).

[14] With this method, mortality increases due to modeled ozone and PM₂.₅ from fCO₂ were 415 (207–620)/yr and 640 (160–1280)/yr, respectively, per 1.07 K (Table 1) or a total of near 1000 (350–1800) per 1.00 K (a 1.1% increase relative to the baseline death rate - Table 1), with about 40% due to ozone. A simple extrapolation from U.S. to world population (301.5 to 6600 million) gives 21,600 (7400–39,000) deaths/yr worldwide per 1 K due to fCO₂ above the baseline air pollution death rate (2.2 million/yr).

The ozone portion of this (8,500 deaths/yr) is conservative compared with 15,500 deaths/yr, calculated from West et al. [2006] (= 30,000 deaths/yr from 1 ppbv ozone multiplied by the 2006:2030 population ratio (66:92) and the ozone
change ratio (0.72:1.0). Remaining differences may be due to different thresholds used (35 ppbv here vs. 25 ppbv).

[15] One estimate of severe weather-related fatalities worldwide in the 1990s was 33,000/yr (Worldwatch Institute, Unnatural disaster: The lesson of Katrina, available at www.worldwatch.org/node/1822, 2005). A 1 K rise will increase this number, but less than 23,000/yr given that hurricane and tornado deaths have declined due to better warning systems (e.g., the deadliest hurricane since 1910 was over 30 years ago – Honduras, 1974, 10,000 deaths). Global warming will increase heat stress- and disease-related deaths as well, but by uncertain rates [e.g., Medina-Ramon and Schwartz, 2007].

[16] fCO\textsubscript{2} increased carcinogens, but the increase was small. Isoprene increases due to higher temperatures increased formaldehyde and acetaldehyde. Reduced dispersion increased exposure to these carcinogens and benzene and 1,3-butadiene.

[17] These simulations treated temperature effects on natural emissions but not power plant or vehicle emissions.

A sensitivity test was run examining the impact of 1 K on power plant energy demand and emissions. The resulting ozone (Figure S4) may cause 80 more U.S. deaths/yr. However, warmer winter temperatures will also decrease natural gas and vehicle emissions, and warmer summers will increase vehicle emissions [Rubin et al., 2006; N. Motallebi et al., manuscript in review, 2007]. The feedbacks of temperature to anthropogenic emissions must be studied more but are expected to be smaller than the other feedbacks examined here. Further uncertainties arise from model resolution, current and future emissions, numerical treatments, health data, and extrapolation of four-month results to a year, as detailed in the auxiliary material.

4. Effects of CO\textsubscript{2} on Stratospheric Ozone and UV Radiation

[18] Whereas, fCO\textsubscript{2} warms the surface and troposphere, it cools the stratosphere (Figure 2a, ii). Measurements indicate a 1%/yr (0.45 ppmv/decade) stratospheric water vapor
increase from 1954–2000 [Rosenlof et al., 2001], but a slight lower-stratospheric decrease from 2001–2005 [Randel et al., 2006]. The simulations here, which accounted for chlorine and bromine gas and heterogeneous chemistry, found that the temperature and H₂O changes due to fCO₂ increased middle and upper-stratospheric ozone but decreased upper tropospheric and lower stratospheric (UTLS) ozone, where its column abundance is greater, causing a net U.S. column ozone loss of 2.7% (Figure 2c, ii, and Table S4). The UTLS ozone losses were due to increases in H₂O there (Figure 2b, ii), as indicated by Figure S2b and Dvortsov and Solomon [2001]. The upper- and middle-stratospheric gains can be explained by Figure S1, which shows that, at 25 km, stratospheric ozone decreases by 1.5% as H₂O increases by 1 ppmv. As temperature decreases by 1.5 K, though, ozone increases by 3.6%, suggesting an overall ozone increase from H₂O and cooling. The ozone increase upon stratospheric cooling is due to increased water vapor and temperatures due to higher CO₂ column ozone loss due to fCO₂. Assuming a higher risk would strengthen the conclusion found here. The all-cause 2003 U.S. death rate of those ≥35 ppbv O₃ was 809.7 deaths/yr per 100,000 total population. No scaling of results from the 4-month model period to the annual average was performed to be conservative, since PM, concentrations from July–November are lower than in the annual average based on California data (H. Tran, personal communication, 2007).

5. Summary

[19] A climate-air pollution model showed by cause and effect that fossil-fuel CO₂ increases increase U.S. surface ozone, carcinogens, and particulate matter, thereby increasing death, asthma, hospitalization, and cancer rates. Increased water vapor and temperatures due to higher CO₂
each increase ozone increasingly with increasing ozone. At low ozone, more water vapor decreases ozone slightly but higher temperatures increase biogenic emission in many areas, offsetting ozone decreases in such areas. CO₂ increases stability, the relative humidity, and biogenic particle mass thus PM_{2.5}. Finally, CO₂ decreases column ozone over the U.S. by increasing upper tropospheric/lower stratospheric water vapor.


References


M. Z. Jacobson, Jacobson, Department of Civil and Environmental Engineering, Stanford University, Stanford, CA 94305-4020, USA. (jacobson@stanford.edu)