

1 On the causal link between carbon dioxide and air 2 pollution mortality

3
4 Mark Z. Jacobson

5 Department of Civil and Environmental Engineering, Stanford University, Stanford,
6 California 94305-4020, USA; Email: jacobson@stanford.edu; Tel: (650) 723-6836

7
8 *Geophysical Research Letters*

9 *Submitted June 22, 2007, Accepted, Dec. 24, 2007, In Press, Jan. 3, 2007*

10
11 Greenhouse gases and particle soot have been linked to enhanced sea-level, snowmelt,
12 disease, heat stress, severe weather, and ocean acidification, but the effect of carbon
13 dioxide (CO₂) on air pollution mortality has not been examined or quantified. Here, it is
14 shown that increased water vapor and temperatures from higher CO₂ separately increase
15 ozone more with higher ozone; thus, global warming may exacerbate ozone the most in
16 already-polluted areas. A high-resolution global-regional model then found that CO₂ may
17 increase U.S. annual air pollution deaths by about 1000 (350-1800) and cancers by 20-30
18 per 1 K rise in CO₂-induced temperature. About 40% of the additional deaths may be due
19 to ozone and the rest, to particles, which increase due to CO₂-enhanced stability,
20 humidity, and biogenic particle mass. An extrapolation by population could render
21 21,600 (7400-39,000) excess CO₂-caused annual pollution deaths worldwide, more than
22 those from CO₂-enhanced storminess.

23 24 **1. Introduction**

25 Because carbon dioxide's (CO₂'s) ambient mixing ratios are too low to affect human
26 respiration directly, CO₂ has not been considered a classic air pollutant. Its effects on
27 temperatures, though, affect meteorology, and both feed back to air pollution. Several

1 studies have modeled the sensitivity of ozone to temperature [*Sillman and Samson*, 1995;
2 *Zhang et al.*, 1998] and the regional or global effects of climate change from all
3 greenhouse gases on ozone [*Thompson et al.*, 1989; *Evans et al.*, 1998; *Dvortsov et al.*,
4 2001; *Mickley et al.*, 2004; *Stevenson et al.*, 2005; *Brasseur et al.*, 2006 *Murazaki and*
5 *Hess*, 2006; *Steiner et al.*, 2006; *Racherla and Adams*, 2006] and aerosol particles [*Aw*
6 *and Kleeman*, 2003; *Liao et al.*, 2006; *Unger et al.*, 2006]. Some studies have highlighted
7 the effect of water vapor on chemistry [*Evans et al.*, 1998; *Dvortsov et al.*, 2001;
8 *Stevenson et al.*, 2005; *Steiner et al.*, 2006; *Racherla and Adams*, 2006; *Aw and Kleeman*,
9 2003]. However, none has isolated the effect of CO₂ alone on ozone, particles, or
10 carcinogens, applied population and health data to the pollution changes, or examined the
11 problem with a global-regional climate/air pollution model.

12 Here, a box photochemistry calculation is first used to show how increases in
13 water vapor and temperature independently increase ozone more with high than low
14 ozone. This analysis helps to explain the causal link between CO₂ and health in areas
15 where most people live, as subsequently found in 3-D global-regional simulations.

16

17 **2. Chemical Effects of CO₂ on Ozone**

18 The SMVGEAR II chemical solver was used first in box mode, without dilution or
19 entrainment, to solve chemistry for 12 hours among 128 gases and 395 inorganic,
20 organic, sulfur, chlorine, and bromine reactions (including 57 photoprocesses) [mostly in
21 *Jacobson*, 2007, Suppl. Mat.]. Cases with different initial NO_x and organic gas were run.

22 Figure 1 shows the water-vapor (H₂O)- and temperature-dependence of ozone
23 under several ozone precursor combinations. For initial NO_x<8 ppbv, ozone decreased
24 with increasing H₂O. For initial NO_x>80 ppbv and moderate initial NO_x with low
25 organics, though, ozone increased with increasing H₂O, by up to 2.8 ppbv-O₃ per 1 ppthv-
26 H₂O. Between these extremes, ozone increased with increasing H₂O at low H₂O and
27 stayed constant or slightly decreased at high H₂O (Supplementary Material). Figure 1 also

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

3 Further, the more ozone present, the more temperature-dependent chemistry
4 increases ozone (Fig. 1), consistent with *Sillman and Samson* [1995] and *Zhang et al.*
5 [1998]. The ozone increase ($\Delta\chi$, ppbv) per 1 K change in temperature (ΔT) from all
6 points in Fig. 1 were fit to

7

$$8 \quad \Delta\chi/\Delta T = -0.13034 - 0.0045585\chi + 0.00028643\chi^2 - 4.6893 \times 10^{-7}\chi^3 \quad (1)$$

9

10 where χ is ozone (ppbv) at 298.15 K (32-250 ppbv). A 1 K rise increased ozone by about
11 0.1 ppbv at 40 ppbv but 6.7 ppbv at 200 ppbv. *Olszyna et al.* [1997] reported an observed
12 correlation in the rural southeast U.S. of 2.4 ppbv ozone per 1 K. If temperature-
13 dependent chemistry alone were causing this increase, ozone would need to be about 115
14 ppbv (Equation 1) in that study, but it was 30-90 ppbv. Thus, other factors not accounted
15 for in Equation 1, such as H₂O increases (described above) and biogenic gas emission
16 increases [e.g., *Guenther et al.*, 1995], due to higher temperatures, may have caused the
17 larger observed temperature-ozone correlation. Also, both temperature and ozone
18 increase with sunlight, so all observed temperature-ozone correlations overestimate the
19 magnitude of cause and effect.

20

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

22 The chemistry used for Fig. 1 was applied with emission, aerosol, cloud, meteorological,
23 radiative, transport, and surface processes in the nested global-urban 3-D model,
24 GATOR-GCMOM. The model (Supplementary Material) has been evaluated against U.S.
25 gas, aerosol, meteorological, and radiative data extensively [e.g., *Jacobson et al.*, 2001;
26 2004; 2007; *Colella et al.*, 2005]. .

1 Two global simulations (4°-SNx5°-WE) were run under present-day conditions. In
2 the second, fossil-fuel CO₂ (fCO₂) ambient mixing ratios and emissions were set to
3 preindustrial values. When U.S. temperatures were about 1 K higher in the present minus
4 preindustrial-CO₂ global simulations, the U.S. regional domain (0.5°S-Nx0.75°W-E) in
5 each global simulation was turned on and initialized with global-domain data (including
6 ambient CO₂). Global and regional domains were run another four months. Emissions of
7 fCO₂ were included in the present-day but not preindustrial-CO₂ global- and U.S.-domain
8 simulations.

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

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

20 In the southeast, 0.5-1 K temperature increases increased isoprene and
21 monoterpenes (Fig. S3a), reducing the relative humidity (Fig. S3c) and cloud optical
22 depth (Fig. S3d), increasing ultraviolet radiation (Fig. S3e), and enhancing ozone. The
23 0.5-2 ppbv/K ozone increase in Tennessee is just below the correlated estimate of 2.4
24 ppbv/K from *Olszyna et al.* [1997] as expected (Section 2). Averaged over the U.S.
25 domain, higher temperatures from fCO₂ increased biogenic soil NO_x, isoprene,
26 monoterpene, and other organic carbon emissions by 6% (0.01 Tg/yr), 9% (0.47), 9.8%
27 (0.15), and 8.9% (0.14), respectively. In the northeast, higher ozone due to higher

1 temperatures was offset partly by higher cloud optical depth (Fig. S3d) and lower
2 ultraviolet radiation (Fig. S3e), modestly increasing ozone.

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

16 Health effect changes (Δy) due to ozone and PM_{2.5} changes in each model cell
17 were determined from [e.g., *Ostro et al.*, 2006],

18

$$19 \Delta y = (1 - \exp[-\beta \Delta x]) y_0 P \quad (2)$$

20

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

26 With this method, mortality increases due to modeled ozone and PM_{2.5} from fCO₂
27 were 415 (207-620)/yr and 640 (160-1280)/yr, respectively, per 1.07 K (Table 1) or a

1 total of near 1000 (350-1800) per 1.00 K (a 1.1% increase relative to the baseline death
2 rate - Table 1), with about 40% due to ozone. A simple extrapolation from U.S. to world
3 population (301.5 to 6600 million) gives 21,600 (7400-39,000) deaths/yr worldwide per 1
4 K due to fCO₂ above the baseline air pollution death rate (2.2 million/yr). The ozone
5 portion of this (8,500 deaths/yr) is conservative compared with 15,500 deaths/yr,
6 calculated from *West et al.* [2006] (=30,000 deaths/yr from 1 ppbv ozone multiplied by
7 the 2006:2030 population ratio (66:92) and the ozone change ratio (0.72:1.0). Remaining
8 differences may be due to different thresholds used (35 ppbv here vs. 25 ppbv).

9 One estimate of severe weather-related fatalities worldwide in the 1990s was
10 33,000/yr [*Worldwatch*, 2005]. A 1 K rise will increase this number, but less than
11 23,000/yr given that hurricane and tornado deaths have declined due to better warning
12 systems (e.g., the deadliest hurricane since 1910 was over 30 years ago – Honduras,
13 1974, 10,000 deaths). Global warming will increase heat stress- and disease-related
14 deaths as well, but by uncertain rates [e.g., *Medina-Ramon and Schwartz*, 2007].

15 FCO₂ increased carcinogens, but the increase was small. Isoprene increases due to
16 higher temperatures increased formaldehyde and acetaldehyde. Reduced dispersion
17 increased exposure to these carcinogens and benzene and 1,3-butadiene.

18 These simulations treated temperature effects on natural emissions but not power
19 plant or vehicle emissions. A sensitivity test was run examining the impact of 1 K on
20 power plant energy demand and emissions. The resulting ozone (Fig. S4) may cause 80
21 more U.S. deaths/yr. However, warmer winter temperatures will also decrease natural gas
22 and vehicle emissions, and warmer summers will increase vehicle emissions [*Rubin et*
23 *al.*, 2006; *N. Motallebi et al.*, manuscript in review 2007]. The feedbacks of temperature
24 to anthropogenic emissions must be studied more but are expected to be smaller than the
25 other feedbacks examined here. Further uncertainties arise from model resolution, current
26 and future emissions, numerical treatments, health data, and extrapolation of four-month
27 results to a year, as detailed in the Supplementary Material.

1

2 **4. Effects of CO₂ on Stratospheric Ozone and UV radiation**

3 Whereas, fCO₂ warms the surface and troposphere, it cools the stratosphere (Fig. 2a.ii).
4 Measurements indicate a 1%/yr (0.45 ppmv/decade) stratospheric water vapor increase
5 from 1954-2000 [Rosenlof *et al.*, 2001], but a slight lower-stratospheric decrease from
6 2001-2005 [Randel *et al.*, 2006]. The simulations here, which accounted for chlorine and
7 bromine gas and heterogeneous chemistry, found that the temperature and H₂O changes
8 due to fCO₂ increased middle and upper-stratospheric ozone but decreased upper
9 tropospheric and lower stratospheric (UTLS) ozone, where its column abundance is
10 greater, causing a net U.S. column ozone loss of 2.7% (Fig. 2c.ii, Table S4). The UTLS
11 ozone losses were due to increases in H₂O there (Fig. 2b.ii), as indicated by Fig. S2b and
12 *Dvortsov and Solomon* [2001]. The upper- and middle-stratospheric gains can be
13 explained by Fig. S1, which shows that, at 25 km, stratospheric ozone decreases by 1.5%
14 as H₂O increases by 1 ppmv. As temperature decreases by 1.5 K, though, ozone increases
15 by 3.6%, suggesting an overall ozone increase from H₂O and cooling. The ozone increase
16 upon stratospheric cooling is due to reduced loss from O+O₃ [Evans *et al.*, 1998]. Despite
17 the column ozone loss due to fCO₂, surface UV hardly changed (Table S4) because fCO₂
18 increased cloud optical depth, offsetting UV increases from ozone loss.

19

20 **5. Summary**

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

1 column ozone over the U.S. by increasing upper tropospheric/lower stratospheric water
2 vapor.

3

4 **Acknowledgements.** NASA grants NNG04GE93G and NNG04GJ89G and U.S.
5 Environmental Protection Agency grant RD-83337101-O. I thank Hien Tran of the
6 California Air Resources Board for helpful health statistic comments.

7

8 **References**

9 Aw, J., and M.J. Kleeman (2003), Evaluating the first-order effect of intraannual
10 temperature variability on urban air pollution, *J. Geophys. Res.*, *108* (D12), 4365,
11 doi:10.1029/2002JD002688.

12 Brasseur, G.P., M.M. Schultz, C. Granier, M. Saunois, T. Diehl, M. Botzet, and E.
13 Roeckner (2006), Impact of climate change on the future chemical composition of the
14 global troposphere, *J. Clim.*, *19*, 3932-3951.

15 Colella, W.G., M.Z. Jacobson, and D.M. Golden (2005), Switching to a U.S. hydrogen
16 fuel cell vehicle fleet: The resultant change in emissions, energy use, and greenhouse
17 gases, *J. Power Sources*, *150*, 150-181.

18 Dvortsov, V.L., and S. Solomon (2001), Response of the stratospheric temperatures and
19 ozone to past and future increases in stratospheric humidity, *J. Geophys. Res.*, *106*,
20 7505-7514 (2001).

21 Evans, S.J., R. Toumi, J.E. Harries, M.P. Chipperfield, and J.M. Russell III (1998),
22 Trends in stratospheric humidity and the sensitivity of ozone to these trends, *J.*
23 *Geophys. Res.*, *103*, 8715-8725.

24 Gaffen, D.J., and R.J. Ross (1999), Climatology and trends of U.S. surface humidity and
25 temperature. *J. Clim.*, *12*, 811-828.

26 Guenther, A., et al. (1995), A global model of natural volatile organic compound
27 emissions, *J. Geophys. Res.*, *100*, 8873-8892.

1 Hoyert, D.L., M.P. Heron, S.L. Murphy, and H.-C. Kung (2006), National Vital Statistics
2 Reports, Vol. 54, No. 13, <http://www.cdc.gov/nchs/fastats/deaths.htm>.

3 Intergovernmental Panel on Climate Change (IPCC), Third Assessment Report, Climate
4 Change 2001: The Scientific Basis, J.T. Houghton *et al.*, eds., Cambridge University
5 Press, New York (2001).

6 Jacobson, M.Z. (2001), GATOR-GCMM: 2. A study of day- and nighttime ozone layers
7 aloft, ozone in national parks, and weather during the SARMAP Field Campaign, *J.*
8 *Geophys. Res.*, *106*, 5403-5420.

9 Jacobson, M.Z., J.H. Seinfeld, G.R. Carmichael, and D.G. Streets (2004), The effect on
10 photochemical smog of converting the U.S. fleet of gasoline vehicles to modern diesel
11 vehicles, *Geophys. Res. Lett.*, *31*, L02116, doi:10.1029/2003GL018448.

12 Jacobson, M.Z., Y.J. Kaufmann, Y. Rudich (2007) Examining feedbacks of aerosols to
13 urban climate with a model that treats 3-D clouds with aerosol inclusions, *J. Geophys.*
14 *Res.*, *112*, doi:10.1029/2007JD008922.

15 Jacobson, M.Z. (2007) Effects of ethanol versus gasoline on cancer and mortality in the
16 United States, *Environ. Sci. Technol.*, *41*, 4150-4157, doi:10.1021/es062085v.

17 Liao, H., W.-T. Chen, and J.H. Seinfeld (2006), Role of climate change in global
18 predictions of future tropospheric ozone and aerosols, *J. Geophys. Res.*, *111*, D12304,
19 doi:10.1029/2005JD006852.

20 Mannino, D.M., D.M. Homa, L.J. Akinbami, J.E. Moorman, C. Gwynn, S.C. Redd
21 (2002), Center for Disease Control Morbidity and Mortality Weekly Report,
22 Surveillance Summaries 51 (SS01); 1-13.

23 Medina-Ramon, M., and J. Schwartz (2007), Temperature, temperature extremes, and
24 mortality: a study of acclimatization and effect modification in 50 U.S. cities, *Occup.*
25 *Environ. Med.*, doi:10.1136/oem.2007.033175.

26 Merrill, C.T., and A. Elixhauser (2005), HCUP Fact Book No. 6: Hospitalization in the
27 United States, 2002. Appendix, www.ahrq.gov/data/hcup/factbk6/factbk6e.htm.

1 Mickley, L.J., D.J. Jacob, B.D. Field, and D. Rind (2004) Effects of future climate
2 change on regional air pollution episodes in the United States, *Geophys. Res. Lett.*, *31*,
3 L24103, doi:10.1029/2004GL021216.

4 Murazaki, K., and P. Hess (2006), How does climate change contribute to surface ozone
5 change over the United States? *J. Geophys. Res.*, *111*, D05301,
6 doi:10.1029/2005JD005873.

7 Olszyna, K.J., M. Luria, and J.F. Meagher (1997), The correlation of temperature and
8 rural ozone levels in southeastern U.S.A., *Atmos. Environ.*, *31*, 3011-3022.

9 Ostro, B.D., H. Tran, and J.I. Levy (2006), The health benefits of reduced tropospheric
10 ozone in California, *J. Air & Waste Manage. Assoc.*, *56*, 1007-1021.

11 Pope, C.A. III, R.T. Burnett, M.J. Thun, E.E. Calle, D. Krewski, K. Ito, and G.D.
12 Thurston (2002), Lung cancer, cardiopulmonary mortality, and long-term exposure to
13 fine particulate air pollution, *JAMA*, *287*, 1132-1141.

14 Racherla, P.N. and P.J. Adams (2006), Sensitivity of global tropospheric ozone and fine
15 particulate matter concentrations to climate change, *J. Geophys. Res.*, *111*, D24103,
16 doi:10.1029/2005JD006939.

17 Randel, W.J., F. Wu, H. Vomel, G.E. Nedoluha, and P. Forster (2006), *J. Geophys. Res.*,
18 Decreases in stratospheric water vapor after 2001: links to changes in the tropical
19 tropopause and the Brewer-Dobson circulation, *111*, D12312,
20 doi:10.1029/2005JD006744.

21 Rosenlof, K.H., et al. (2001), Stratospheric water vapor increases over the past half
22 century. *Geophys. Res. Lett.*, *28*, 1195-1198.

23 Rubin, J.I., Andrew J. Kean, R.A. Harley, D.B. Millet, and A.H. Goldstein (2006),
24 Temperature dependence of volatile organic compound evaporative emissions from
25 motor vehicles, *J. Geophys. Res.*, *111*, D03305, doi:10.1029/2005JD006458.

26 Sillman, S. and P.J. Samson (1995), Impact of temperature on oxidant photochemistry in
27 urban, polluted rural, and remote environments, *J. Geophys. Res.*, *100*, 11,497-11,508.

1 Steiner, A.L., S. Tonse, R.C. Cohen, A.H. Goldsten, and R.A. Harley (2006), Influence of
2 future climate and emissions on regional air quality in California, *J. Geophys. Res.*,
3 *111*, D18303, doi:10.1029/2005JD006935.

4 Stevenson, D., R. Doherty, M. Sanderson, C. Johnson, B. Collins, and D. Derwent
5 (2005), Impacts of climate change and variability on tropospheric ozone and its
6 precursors. *Faraday Disc.*, *130*, 1-17.

7 Thompson, A.M., R.W. Stewart, M.A. Owens, and J.A. Herwehe (1989), Sensitivity of
8 tropospheric oxidants to global chemical and climate change, *Atmos. Environ.*, *23*, 519-
9 532.

10 Thorne, P.W., D.E. Parker, D.E., S.F.B. Tett, P.D. Jones, M. McCarthy, H. Coleman, and
11 P. Brohan (2005), Revisiting radiosonde upper-air temperatures from 1958 to 2002. *J.*
12 *Geophys. Res.*, *110*, D18105, doi:10.1029/2004JD005753.

13 Thurston, G.D., and K. Ito (2001), Epidemiological studies of acute ozone exposures and
14 mortality, *J. Exposure Analysis and Env. Epidemiology*, *11*, 286-294.

15 Unger, N., D.T. Shindell, D.M. Koch, M. Ammann, J. Cofala, and D.G. Streets (2006),
16 Influences of man-made emissions and climate changes on tropospheric ozone,
17 methane, and sulfate at 2030 from a broad range of possible futures, *J. Geophys. Res.*,
18 *111*, D12313, doi:10.1029/2005JD006518.

19 West, J.J., A.M. Fiore, L.W. Horowitz, and D.L. Mauzerall (2006) Global health benefits
20 of mitigating ozone pollution with methane emission controls, *Proc. Nat. Acad. Sci.*,
21 *103*, 3988-3993.

22 Worldwatch Institute (2005), Unnatural disaster: The lesson of Katrina,
23 www.worldwatch.org/node/1822.

24 Zhang, Y., C.H. Bischof, R.C. Easter, and P.-T. Wu, Sensitivity analysis of a mixed
25 phase chemical mechanism using automatic differentiation, *J. Geophys. Research*, *103*,
26 18,953-18,797 (1998).
27

Figure Captions

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18

Figure 1. Mixing ratio of ozone and several other gases as a function of water vapor mixing ratio after 12 hours of a box-model chemistry-only simulation initialized at 0430 under several initial NO_x and nonmethane organic gas (NMOG) mixing ratio combinations (ppbv) (given in the figure) at 298.15 K (solid lines) and 299.15 K (dashed lines). The simulations assumed sinusoidally varying photolysis between 0600 and 1800.

Figure 2. Four-month (mid-July to mid-November) domain-averaged near-surface and vertical-profile differences in (a) temperature, (b) water vapor, and (c) ozone between the present-day and preindustrial- CO_2 simulations. The domain-averaged (over land and water) change for each surface plot is given in parentheses. Also shown in Fig. 2a.ii is the 1958-2006 globally-averaged radiosonde temperature change [*Thorne et al.*, 2005], which is for reference only since the present simulations isolate the effects of CO_2 and do not examine all forcing agents.

1 **Table 1.** Summary of CO₂'s effects on cancer, ozone mortality, ozone hospitalization,
2 ozone emergency-room (ER) visits, and particulate-matter mortality. Results are shown
3 for the present-day ("Base") and present-day minus preindustrial ("no-fCO₂") 3-D
4 simulations. All mixing ratios and concentrations are near-surface values averaged over
5 four months (mid-July to mid-November) and weighted by population (!). Divide the last
6 column by 1.07 K (the population-weighted CO₂-induced temperature change from Table
7 S4) to obtain the health effect per 1 K.

	Base	Base minus no fCO ₂
Carcinogens		
Formaldehyde (ppbv)	3.61	+0.22
Acetaldehyde (ppbv)	2.28	+0.203
1,3-Butadiene (ppbv)	0.254	+0.00823
Benzene (ppbv)	0.479	+0.0207
USEPA cancers/yr ⁺	389	+23
OEHHA cancers/yr ⁺	789	+33
Ozone		
8-hr ozone (ppbv) in areas ≥35 ppbv%	42.3	+0.724
Pop (mil.) exposed in areas ≥35 ppbv#	184.8	184.8
High ozone deaths/yr*	6230	620
Med. ozone deaths/yr*	4160	+415
Low ozone deaths/yr*	2080	+207
Ozone hospitalizations/yr*	24,100	+2400
Ozone ER visits/yr*	21,500	+2160
Particulate matter		
PM2.5 (µg/m ³) in areas > 0 µg/m ³ \$	16.1	+0.065
Pop (mil.) exposed in areas ≥ 0 µg/m ³	301.5	301.5
High PM2.5 deaths/yr^	191,000	+1280
Medium PM2.5 deaths/yr^	97,000	+640
Low PM2.5 deaths/yr^	24,500	+160

8 (!) A population-weighted value is defined in the footnote to Table S4.

1 (+) USEPA and OEHHA cancers/yr were found by summing the product of individual CUREs (cancer unit
2 risk estimates=increased 70-year cancer risk per $\mu\text{g}/\text{m}^3$ sustained concentration change) by the
3 population-weighted mixing ratio or mixing ratio difference of a carcinogen, by the population, and air
4 density, over all carcinogens, then dividing by 70 yr. USEPA CURES are 1.3×10^{-5} (formaldehyde),
5 2.2×10^{-6} (acetaldehyde), 3.0×10^{-5} (butadiene), 5.0×10^{-6} (=average of 2.2×10^{-6} and 7.8×10^{-6}) (benzene)
6 (www.epa.gov/IRIS/). OEHHA CUREs are 6.0×10^{-6} (formaldehyde), 2.7×10^{-6} (acetaldehyde), 1.7×10^{-4}
7 (butadiene), 2.9×10^{-5} (benzene) (www.oehha.ca.gov/risk/ChemicalDB/index.asp).

8 (%) 8-hr ozone ≥ 35 ppbv is the highest 8-hour-averaged ozone during each day, averaged over all days of
9 the four-month simulation in areas where this value ≥ 35 ppbv in the base case. When base $\text{O}_3 > 35$ ppbv
10 and no-f CO_2 $\text{O}_3 < 35$ ppbv, the mixing ratio difference was base O_3 minus 35 ppbv.

11 (#) The 2007 population exposed to ≥ 35 ppbv O_3 is the population exposed to a four-month-averaged 8-
12 hour averaged ozone mixing ratio above 35 ppbv and was determined from the base case.

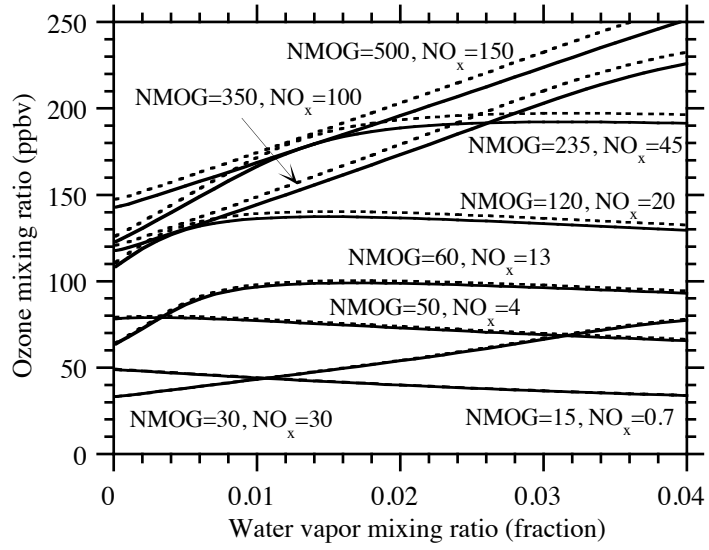
13 (*) High, medium, and low deaths/yr, hospitalizations/yr, and emergency-room (ER) visits/yr due to short-
14 term O_3 exposure were obtained from Eq. 2 applied to each model cell, summed over all cells. The
15 baseline 2003 U.S. death rate (y_0) was 833 deaths/yr per 100,000 [Hoyert *et al.*, 2006]. The baseline 2002
16 hospitalization rate due to respiratory problems was 1189 per 100,000 [Merrill and Elixhauser, 2005].
17 The baseline 1999 all-age emergency-room visit rate for asthma was 732 per 100,000 [Mannino *et al.*,
18 2002]. These rates were assumed to be the same in each U.S. county, although they vary slightly by
19 county. The fraction increases (β) in the number of deaths from all causes due to ozone were 0.006,
20 0.004, and 0.002 per 10 ppbv increase in daily 1-hr maximum ozone [Ostro *et al.*, 2006]. These were
21 multiplied by 1.33 to convert the risk associated with 10 ppbv increase in 1-hr maximum O_3 to that
22 associated with a 10 ppbv increase in 8-hour average O_3 [Thurston and Ito, 2001]. The central value of
23 the increased risk of hospitalization due to respiratory disease was 1.65% per 10 ppbv increase in 1-hour
24 maximum O_3 (2.19% per 10 ppbv increase in 8-hour average O_3), and that for all-age ER visits for
25 asthma was 2.4% per 10 ppbv increase in 1-hour O_3 [Ostro *et al.*, 2006] (3.2% per 10 ppbv increase in 8-
26 hour O_3). All values were reduced by 45% to account for the mid-July to mid-November and year-around
27 $\text{O}_3 > 35$ ppbv ratio, obtained from detailed observations [H. Tran, *pers. comm.*].

28 (\$) This is the simulated 24-hr $\text{PM}_{2.5}$, averaged over four months, in locations where $\text{PM}_{2.5} \geq 0 \mu\text{g}/\text{m}^3$.

29 (^) The death rate due to long-term $\text{PM}_{2.5}$ exposure was calculated from Eq. 2. Pope *et al.*, [2002] provide
30 increased death risks to those ≥ 30 years of 0.008 (high), 0.004 (medium), and 0.001 (low) per $1 \mu\text{g}/\text{m}^3$
31 $\text{PM}_{2.5} > 8 \mu\text{g}/\text{m}^3$ based on 1979-1983 data. From $0-8 \mu\text{g}/\text{m}^3$, the increased risks were conservatively but
32 arbitrarily assumed $=\frac{1}{4}$ those $> 8 \mu\text{g}/\text{m}^3$ to account for reduced risk near zero $\text{PM}_{2.5}$. Assuming a higher
33 risk would strengthen the conclusion found here. The all-cause 2003 U.S. death rate of those ≥ 30 years
34 was 809.7 deaths/yr per 100,000 total population. No scaling of results from the 4-month model period to
35 the annual average was performed to be conservative, since $\text{PM}_{2.5}$ concentrations from July-November
36 are lower than in the annual average based on California data [H. Tran, *pers. comm.*].

37

1 **Figure 1.**
2
3



4
5
6
7

Figure 2.

