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Low-carbon energy generates public health savings in California

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Abstract. California's goal to reduce greenhouse gas (GHG) emissions to a level that is 80 % below 1990 levels by the year 2050 will require adoption of low-carbon energy sources across all economic sectors. In addition to reducing GHG emissions, shifting to fuels with lower carbon intensity will change concentrations of short-lived conventional air pollutants, including airborne particles with a diameter of less than 2.5 µm ($PM_{2.5}$) and ozone (O_3). Here we evaluate how business-as-usual (BAU) air pollution and public health in California will be transformed in the year 2050 through the adoption of low-carbon technologies, expanded electrification, and modified activity patterns within a low-carbon energy scenario (GHG-Step). Both the BAU and GHG-Step statewide emission scenarios were constructed using the energy–economic optimization model, CA-TIMES, that calculates the multi-sector energy portfolio that meets projected energy supply and demand at the lowest cost, while also satisfying scenario-specific GHG emissions constraints. Corresponding criteria pollutant emissions for each scenario were then spatially allocated at 4 km resolution to support air quality analysis in different regions of the state. Meteorological inputs for the year 2054 were generated under a Representative Concentration Pathway (RCP) 8.5 future climate. Annual-average $PM_{2.5}$ and O_3 concentrations were predicted using the modified emissions and meteorology inputs with a regional chemical transport model. In the final phase of the analysis, mortality (total deaths) and mortality rate (deaths per 100 000) were calculated using established exposure-response relationships from air pollution epidemiology combined with simulated annual-average $PM_{2.5}$ and O_3 exposure. Net emissions reductions across all sectors are −36 % for $PM_{0.1}$ mass, −3.6 % for $PM_{2.5}$ mass, −10.6 % for $PM_{2.5}$ elemental carbon, −13.3 % for $PM_{2.5}$ organic carbon, −13.7 % for NO_x, and −27.5 % for NH_3. Predicted deaths associated with air pollution in 2050 dropped by 24–26 % in California (1537–2758 avoided deaths yr^{-1}) in the "climate-friendly" 2050 GHG-Step scenario, which is equivalent to a 54–56 % reduction in the air pollution mortality rate (deaths per 100 000) relative to 2010 levels. These avoided deaths have an estimated value of USD 11.4–20.4 billion yr^{-1} based on the present-day value of a statistical life (VSL) equal to USD 7.6 million. The costs for reducing California GHG emissions 80 % below 1990 levels by the year 2050 depend strongly on numerous external factors such as the global price of oil. Best estimates suggest that meeting an intermediate target (40 % reduction in GHG emissions by the year 2030) using a non-optimized scenario would reduce personal income by USD 4.95 billion yr^{-1} (−0.15 %) and lower overall state gross domestic product by USD 16.1 billion yr^{-1} (−0.45 %). The public health benefits described here are comparable to these cost estimates, making a compelling argument for the adoption of low-carbon energy in California, with implications for other regions in the United States and across the world.

1 Introduction

Implementation of California's climate policy (Executive Order S-3-05) to reduce GHG emissions 80 % below 1990 levels by the year 2050 will require widespread adoption of low-carbon energy supply and demand technologies across the state's entire economy. These changes will not only reduce California's contribution to climate change, they will also alter the chemical composition, spatial pattern, and attributable adverse health effects of the state's serious air pollution problem. Reducing long-term exposure to fine airborne particulate matter ($PM_{2.5}$) and ozone (O_3) will improve public

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health through a reduction in premature mortality (Krewski et al., 2009; Lepeule et al., 2012).

California's near-term measures to mitigate greenhouse gas (GHG) emissions are required by the Global Warming Solutions Act of 2006 (Assembly Bill (AB) 32). Since the adoption of AB 32, a wave of incentives, mandates, carbon markets, fees, and standards have been implemented to curb the rate of the state's GHG emissions. Regulations include the Renewables Portfolio Standard for the electricity generation sector, the Low Carbon Fuel Standard aimed at reducing carbon intensity of transport fuels, the Pavley Clean Car Standards for fuel economy and CO_2 emissions, and the Cap-and-Trade Program. Zapata et al. (2012) analyzed the air quality co-benefits of AB 32 and found that the GHG mitigation measures had the co-benefit of reducing $PM_{2.5}$ concentrations in California by $\sim 6\,\%$ in the year 2030 with a corresponding decrease in mortality due to air pollution. Additional measures will be needed to meet the targets included in California's Executive Order S-3-05 that calls for GHG emissions to decrease 80 % below 1990 GHG levels by the year 2050.

Numerous previous studies have examined the relationship between climate policies and air quality using methods tailored to match the region of interest (Table S1 in the Supplement). For example, Jacobson et al. (2014, 2015) examined how a scenario of 100 % wind, water, and solar would alter all economic sectors, leading to changes in air quality and health impacts for California and the United States in 2050. This bounding analysis is extremely valuable since it quantifies the maximum possible air quality benefits associated with climate policies, but a recent analysis suggests that scenarios incorporating a broader range of technologies may be more realistic (Clack et al., 2017). The debate on this point is ongoing (Jacobson et al., 2017). For studies that consider a broad range of technologies, multiple approaches have been used to select between the diverse technologies available in these future scenarios, but the majority of these studies rely on the expert opinions of the authors rather than an objective analysis. For example, Shindell et al. (2012) created a future scenario by selecting measures that were "assumed to improve air quality" and mitigate both long-lived GHGs and short-lived criteria pollutants after ranking them by climate impact. The extensive study by van Aardenne et al. (2010) explored six scenarios with wider levels of air and/or climate policy, as well as the option of biofuel consumption; however, technology adoption is again largely dependent on author-specified assumptions on shares of existing technologies. Since the technology choices in each scenario strongly affect the air quality outcomes, the author assumptions in these previous studies have a strong influence on the calculated health benefits stemming from reduced air pollution concentrations. As a secondary limitation, many previous studies have been carried out for regions much larger than California which requires the use of coarse grid cells that do not completely resolve important spatial patterns of pollutants within the state's complex topography (West et al., 2013; Garcia-Menendez et al., 2015).

Here we build on the previous work on climate policy–air quality interactions by conducting an optimized emissions analysis at high spatial resolution for California. The state of California has a very large and diverse economy and so it is difficult to design optimal GHG mitigation strategies using expert opinions alone. Energy–economic optimization models are needed to find least-cost scenarios that achieve GHG objectives within the resource constraints of the state. California also has significant existing environmental regulations and so detailed analysis is required to account for the impact of technology, fuel, and behavioral changes implied by broad GHG policies on the landscape of preexisting rules. All of this analysis must be carried out at high spatial resolution to properly calculate air pollution exposure in major cities that often experience a sharp gradient of pollutant concentrations across their boundaries.

Zapata et al. (2017) used the CA-REMARQUE (California Regional Multisector Air Quality Emissions) model to predict criteria pollutant emissions associated with two economically optimized scenarios for California in the year 2050: (i) a business-as-usual (BAU) scenario that includes all existing environmental laws in California including AB 32 and (ii) a greenhouse gas mitigation (GHG-Step) scenario including additional least-cost policy and technology adoption needed to achieve the 80 % GHG reduction objective of Executive Order S-3-05 using a CO_2 constrained step function. The results indicated that adoption of the measures in the GHG-Step scenario could cause decreases or increases in criteria pollutant emissions in different economic sectors and locations due to the trade-offs involved in the statewide cost minimization approach. As a further complication, switching to alternative lower-carbon-intensive fuels in the GHG-Step scenario altered the composition of reactive organic gas emissions and the size and composition of particulate matter emissions. These findings reinforce the need for sophisticated analysis methods in complex regions like California.

The overall goal of the present study is to quantify air pollution and health implications associated with the BAU and GHG-Step scenarios described by Zapata et al. (2017) acting across the entire California energy economy in the year 2050. The air pollution concentrations associated with the BAU and GHG-Step scenarios are calculated at 4 km resolution using a regional chemical transport model and the avoided mortality is estimated using established relationships from air pollution epidemiology. Economic benefits are then calculated with the value of a statistical life (VSL). Finally, the total public health benefits from avoided air pollution are compared to the total incremental cost for adoption of low-carbon energy in California to better understand the net costs for the GHG mitigation program.

2 Methodology

Air quality and health impacts associated with energy scenarios in the year 2050 were determined by combining estimated changes to criteria pollutant emissions inventories with downscaled meteorology as inputs to a regional air quality model to predict air quality with 4 km resolution over California. Epidemiology risk exposure functions and mortality data were then used to estimate premature deaths. Figure 1 summarizes the calculations with additional details provided below.

2.1 Criteria pollutant emissions

Criteria pollutant emissions were predicted with the California Regional Multisector Air Quality Emissions (CA-REMARQUE) model (Zapata et al., 2017) for the BAU and GHG-Step scenarios. Both scenarios were constructed using CA-TIMES, a technology-rich, bottom-up, energy economics model that determines the least-cost mix of technology–fuel options for all sectors of the statewide economy. CA-REMARQUE translated these behavior, technology, and fuel changes into spatially and temporally resolved criteria pollutant emissions inventories. CA-REMARQUE predicted that adoption of the GHG-Step policies in place of the BAU policies would cause decreases in emissions of primary $PM_{0.1}$ (−36 %), $PM_{2.5}$ (−3.6 %), oxides of nitrogen (NO_x, −13.7 %), and ammonia (NH_3, −27.5 %) but cause increases in emissions of carbon monoxide (CO, +37 %) and oxides of sulfur (SO_x, +14 %). Some components of primary $PM_{2.5}$ emissions responded more strongly to different technology changes yielding nonuniform reductions of $PM_{2.5}$ elemental carbon (elemental carbon, −10.6 %), $PM_{2.5}$ organic carbon (organic carbon, −13.3 %), and $PM_{2.5}$ copper (Cu, −63 %). The spatial allocation of emission rates was determined by either using existing 4 km spatial patterns of emissions sources or finding new optimal locations for new emissions sources such as biorefineries that were placed near high-biomass-feedstock regions. The future BAU and GHG-Step scenarios considered in the present study do not include nuclear or coal-fired (with or without carbon capture and sequestration) electricity generation in California. Electricity generation in the 2050 GHG-Step scenario is dominated by wind (34 %), solar (34 %), and natural gas (18 %) with smaller contributions from tidal, geothermal, and hydro. A comprehensive analysis of all emissions changes including spatial plots is provided by Zapata et al. (2017).

2.2 Meteorology fields

Meteorology simulations using the Weather Research and Forecasting (WRF) model v3.2.1 (University Corporation of Atmospheric Research 2010) conducted previously (Zhang et al., 2014) for the years 2048–2054 were used as meteorological inputs in this study. Hourly-averaged fields describing spatial and temporal wind speed and direction, humidity, temperature, planetary boundary layer height, downward shortwave radiation, air density, and precipitation were formatted for use with the regional chemical transport model. The 2054 calendar year was the median year over the period 2048–2054 for domain-average $PM_{2.5}$ concentrations within the South Coast Air Basin that contains the majority of the population in California. The focus of the current study is to evaluate how the emissions changes lead to different air quality outcomes. Both emissions scenarios are evaluated using the same meteorology, which minimizes the variability introduced by the climate signal.

2.3 Regional chemical transport model configuration and simulation

Air quality was simulated using the UCD-CIT (University of California, Davis – California Institute of Technology) 3-D regional chemical transport model (Kleeman and Cass, 2001; Ying et al., 2007; Hu et al., 2015). The SAPRC11 (Carter and Heo, 2012; Carter et al., 2012) chemical mechanism was used to represent gas-phase chemical reactions. Gas-to-particle conversion was simulated as a dynamic process based on the concentration of semi-volatile gas-phase compounds at the particle surface in equilibrium with the condensed material inside each particle. Thermodynamic equilibrium within each particle for inorganic species was calculated using the ISORROPIA model (Nenes et al., 1998). Thermodynamic equilibrium within each particle for organic species was calculated using a two-product model (Carlton et al., 2010). Particulate matter emissions profiles include 18 organic, inorganic, and metal particulate species distributed across 15 size bins.

Air quality simulations were conducted over three horizontal domains, a coarse 24 km parent domain, and two 4 km resolution child domains. The coarse domain covered all of California and the adjacent Pacific Ocean to provide boundary inputs to the higher-resolution child domains over populated regions in northern and southern California. A total of 16 telescoping vertical layers were used up to a total height of 5 km above ground. Simulations were conducted for the first 28–29 days of each month for the 2054 calendar year. The first 3 days of every month were excluded to minimize the effects of initial conditions which are not known exactly, leaving 301 simulation days to be used in the statistical analysis.

2.4 Population projections

A 2050 California population projection at 4 km spatial resolution was used for both population-weighted concentration estimates and mortality estimates. This population projection is based on the highly resolved block-group 2010 census population data in shapefile format (US Census Bureau) which was intersected with the regular air quality grid. The

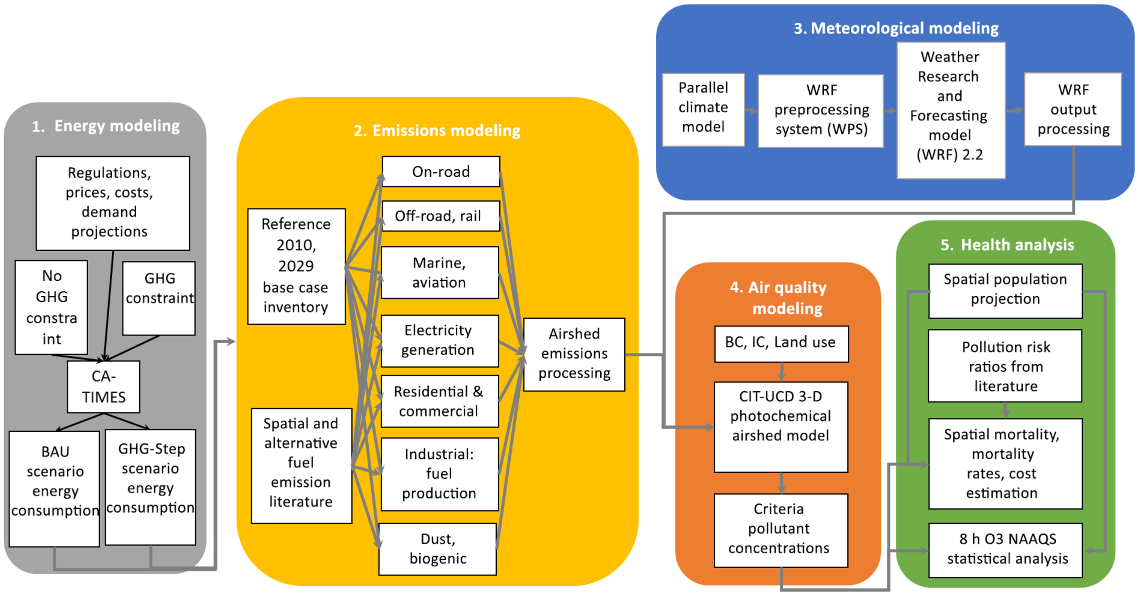

Figure 1. Process diagram of sequence of stages for modeling and analysis.

4 km resolution population field was then scaled according to the projected populations for each county in 2050 (California Department of Finance. Demographic Research Unit 2014) relative to 2010 (Table S2). This procedure was conducted separately for population age >35 and for all ages (see Fig. S1) to be used for the population-weighted code (all ages) and the mortality estimates (>35 years). The combined southern and northern 4 km resolution modeling domains encompassed 92 % of California's projected 2050 population (summarized in Table S3).

Population acts as a spatial surrogate for distributing emissions and as a receptor for calculating the public health effects of air pollution. Consistent population fields were used for both of these tasks in the current study. Population growth rates by county are summarized by Zapata et al. (2017).

2.5 Statistical and exceedance analysis

Several statistical analyses were conducted across space, seasons, and scenarios. Annual-average concentration plots were estimated by taking the average of 301 daily concentration fields. A two-tailed paired t test was used to identify significant differences between BAU and GHG-Step concentrations. Annual or seasonal concentration field plots were condensed to a statewide, air basin, or county population-weighted concentration estimate by summing the concentration multiplied by the population in each cell and then dividing the resulting sum by the entire population for the region of interest.

Daily maximum 8 h average O_3 concentrations were calculated for each model grid cell. Subsequent seasonal or annual averages used the daily maximum 8 h average concentrations for a given state, basin, or county. To determine whether a county was in compliance with the 70 ppb O_3 National Ambient Air Quality Standards (NAAQS), the fourth highest population-weighted maximum 8 h O_3 concentration was calculated. The number of days exceeding this standard was also tabulated.

2.6 Mortality and cost estimates

Premature mortality estimates from long-term exposure to $PM_{2.5}$ and O_3 were calculated using annual-average 4 km resolution concentration fields for the BAU and GHG-Step scenarios. The attributable fraction (AF) is the portion of deaths or incidences that can be associated with the cause of interest, in this case the fraction of deaths due to annual $PM_{2.5}$ and O_3 exposure. The AF quantifies the change in the relative risk.

$$\mathrm{AF}_i = \frac{\mathrm{RR}_i - 1}{\mathrm{RR}_i} = \frac{e^{\beta(x_i - x_{i,\mathrm{bkg}})} - 1}{e^{\beta(x_i - x_{i,\mathrm{bkg}})}} \quad (1)$$

The log-linear incidence rate function is assumed when calculating the risk ratio (RR) as shown in Eq. (1). The beta coefficient (β) is derived from taking the natural log of the RR found in epidemiology literature. $PM_{2.5}$ RR for all-cause mortality associated with a 10 µm m^{-3} increase in long-term $PM_{2.5}$ exposure is estimated at 1.062 based on a worldwide meta-analysis (Hoek et al., 2013) or 1.036 based on the American Cancer Society follow-up (Krewski 2009). An O_3 RR of 1.04 for respiratory mortality from long-term O_3 exposure is based on Jerrett et al. (2009). The change in concentration is based on taking the annual-average concentration for a given grid cell (x_i) and subtracting it from the background concentration ($x_{i,\mathrm{bkg}}$). Background concentrations on the west coast of North America are often measured

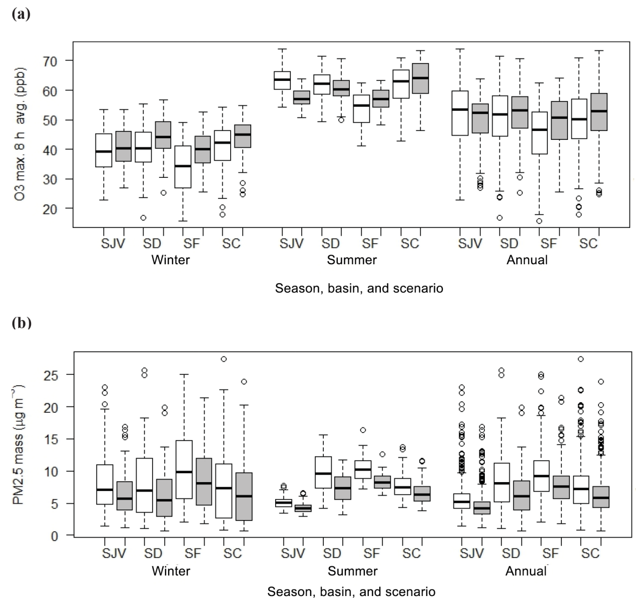

Figure 2. **(a)** Population-weighted 8 h average ozone concentration by region. **(b)** Population-weighted $PM_{2.5}$ mass concentration by region. Averages are shown for the winter, summer, and annual time periods in the year 2054. SJV, SD, SF, and SC represent the San Joaquin Valley, San Diego, San Francisco, and South Coast, respectively. A P value < 0.0001 was found for each difference between concentrations calculated with the BAU emissions (white bars) versus the GHG-Step emissions (gray bars).

at mountain sites that sample the free troposphere. Herner et al. (2005) measured $PM_{1.8}$ concentrations of 4 µg m^{-3} at Sequoia National Park (elevation 535 m) during periods when this site was in the free troposphere. McKendry (2006) surveyed published literature and reviewed monitoring data in British Columbia on the west coast of North America and estimated that background $PM_{2.5}$ concentrations are 2 µm m^{-3} with little evidence of change over time. A background $PM_{2.5}$ concentration of 3 µm m^{-3} and O_3 concentration of 35 ppb was assumed in the current study. The beta coefficient, change in cell concentration, is then used to calculate the risk ratio (RR_i) and subsequently the AF.

$$E_s = \sum_i AF_i B_c P_i \tag{2}$$

The mortality (E_s) for each scenario for a given region was calculated using Eq. (2) by taking the product of the population and mortality rate to get the deaths, followed by multiplying the fraction that is attributable to pollution (see Eq. 1). Population (P_i) projections for ages 35 and older were used in this calculation due to high uncertainty for younger age groups. Averaged 2009–2013 California all-cause (all ICD 10 codes) and respiratory (ICD 10 codes J0–J98) mortality rates (B_c), calculated in deaths per 100 000, were determined for each California county for ages 35 and older from the CDC WONDER database (United States Department of Health and Human Services (US DHHS) et al., 2014).

Costs associated with premature death from long-term air pollution exposure were estimated using the VSL method, assuming that a death equates to USD 7.6 million, based on the distribution of 26 economic reports (Viscusi and Aldy 2003) and the suggested value by the EPA (Industrial Economics, 2011; Bart Ostro, personal communication, 2015; RTI International 2015). This value can be adjusted to a future year with an average discount rate "i" by multiplying with the value $(1+i)^{\text{future year}-\text{base year}}$, where the base year is 2006. VSL is estimated based on a willingness to pay for small reductions in mortality risk through the selection of different job types. "Willingness to pay" estimates are thought to incorporate "cost of illness" including morbidity but they do not capture non-health damage.

3 Results and discussion

3.1 Ozone (O_3) concentration

3.1.1 Annual average and seasonal ozone changes

Figure 2a shows the population-weighted daily maximum 8 h ozone concentrations for the 2054 meteorological year under the BAU and GHG-Step emissions scenarios. Box and whisker plots are shown for winter, summer, and annual time periods to consider both cyclical and yearly effects. Figure 3a illustrates the spatial distribution of ozone concentrations in the BAU scenario while Fig. 3b illustrates the changes induced by the GHG-Step scenario. The annual-average BAU 8 h ozone concentration reaches a maximum of 61 ppb in Southern California downwind (east) of Los Angeles and San Bernardino. In the northern-central California domain, the annual-average BAU 8 h ozone concentration has a maximum value of 57 ppb along the Northern Central Coast Air Basin, around Santa Clara and San Benito County.

Figure 3b illustrates that regional 8 h average ozone concentrations (annually averaged) in the San Joaquin Valley (SJV) air basin (containing the cities of Bakersfield and Fresno) decrease by 2–3 ppb under the GHG-Step scenario. GHG mitigation strategies did not reduce ozone concentrations in major population centers including the San Francisco (SF) air basin and the South Coast (SC) Air Basin (containing the city of Los Angeles). To the contrary, ozone concentrations increased in these dense urban regions because BAU conditions have excess NO_x concentrations that titrate ozone. The extent of NO_x emission reductions under the GHG-Step scenario is insufficient to shift the chemical regime to one in which decreases in NO_x lead to O_3 reductions, instead favoring more ozone formation (Seinfeld and Pandis, 2006).

Figure 2a illustrates that population-weighted annual-average 8 h ozone concentrations in the rural SJV decreased

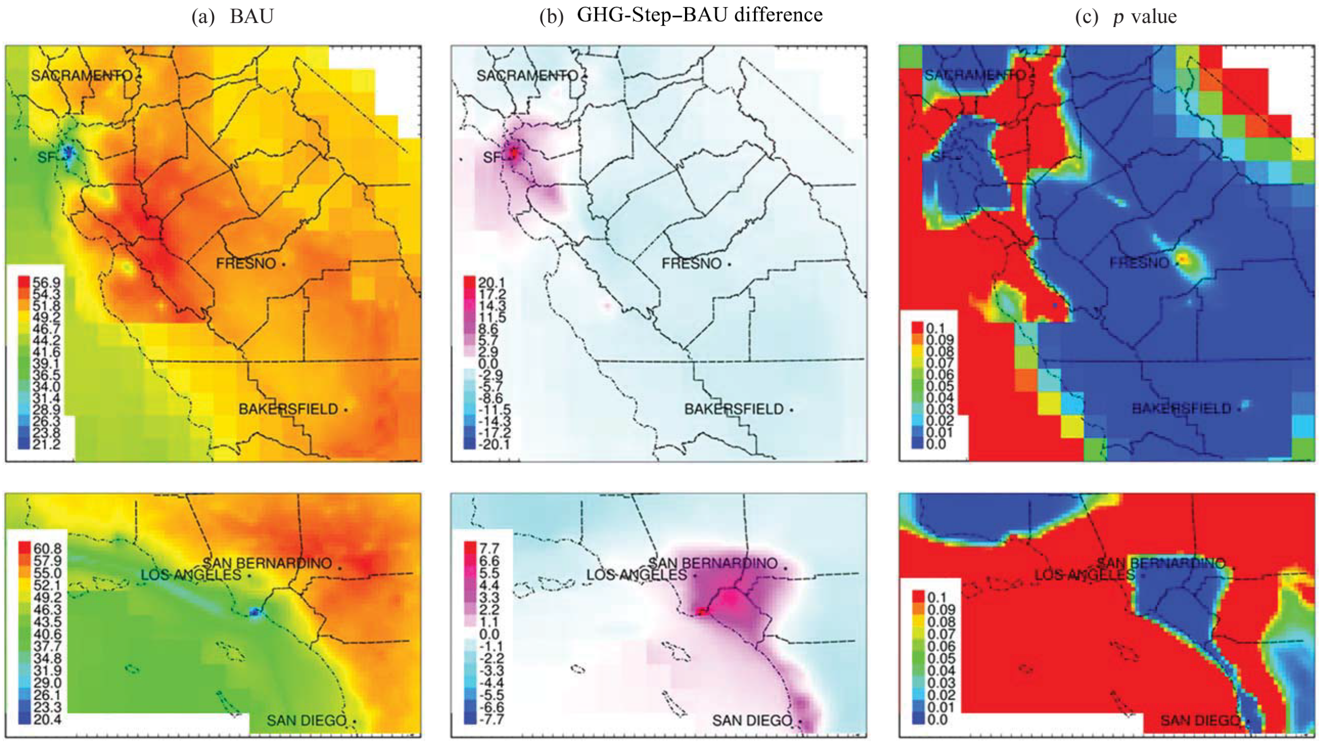

Figure 3. (a) Annual average of daily 8 h average ozone concentration (ppb) under the BAU scenario, **(b)** change in 8 h average ozone concentrations (ppb) under the GHG-Step scenario, and *p*-value significance level of the difference between concentrations predicted using the BAU and GHG-Step scenarios. All simulations for the year 2054. Both 24 km resolution results and the finer 4 km resolution results are shown, with the finer, smaller southern California or central-northern California domains overlaid upon the coarse California domain results.

by −4.3 % (52 to 50 ppb) in the GHG-Step scenario with the greatest reductions occurring in the summer months (−9.4 %). In contrast, population-weighted annual-average 8 h ozone concentrations increased in urbanized regions (SC +5.1 %, San Diego (SD) +2.8 %, SF +6.5 %) consistent with the regional trends illustrated in Fig. 3b. Population-weighted ozone concentrations under the GHG-Step scenario increased in SC, SD, and SF during winter (+7.0, +9.3, and +17 %, respectively) but had mixed trends during summer: ozone concentrations in SC and SF (highest population density) increased by +3.2 and +6.1 %, respectively, under the GHG-Step scenario but concentrations in SD (slightly lower population density) decreased −2.2 % during the summer season.

Overall, a statewide increase of +3.9 % in population-weighted annual-average 8 h ozone concentrations occurred under the GHG-Step scenario because increased ozone concentrations in heavily populated SF, SC, and SD overwhelmed decreased ozone concentrations in the SJV. The regulatory and health implications of this finding will be discussed in subsequent sections.

3.1.2 High ozone events and number of exceedance days

Most benchmarks for ozone concentrations decrease strongly across California in the 2050 BAU scenario relative to current 2010 levels. Simulations carried out using identical 2010 summer meteorological fields but different emissions inputs (2010 vs. 2050) demonstrate that emission changes – rather than weather inputs – were the primary cause of these decreasing O_3 concentrations. Table 1 summarizes the fourth highest maximum 8 h average ozone concentration and the number of days exceeding the 70 ppb 8 h average ozone standard for different California counties. The fourth highest 8 h average O_3 concentration of each year, averaged over 3 years, is used to determine if a given area is in compliance with the NAAQS. Many California air districts violate the 8 h O_3 NAAQS, with classifications ranging from moderate, serious, severe, to extreme levels of O_3 (Table S4). The county median of the fourth highest 8 h simulated ozone concentration in 2010 is 92.2 ppb (interquartile range (IQR): 74.0–99.1 ppb) with 23 out of 26 counties analyzed reaching levels ≥ 70 ppb. The county median of the fourth highest 8 h average ozone concentration in the 2050 BAU scenario decreases to 69.2 ppb (IQR: 66.2–71.9 ppb) with a further decrease to 64.2 ppb (IQR: 62.8–66.4 ppb) in the GHG-Step scenario.

Table 1. The fourth highest maximum daily 8 h average ozone concentration and number of days exceeding the standard during June–August months. Counties with fourth highest 8 h ozone concentrations ≥ 70 ppb are shown in bold. See Table S4 for 2010 O_3 designation values and areas.

Basin	County or statewide	Fourth highest 8 h O_3 conc. (ppb)			No. of days exceeding 8 h std. of 70 ppb		
		2010	2050 BAU	2050 GHG-Step	2010	2050 BAU	2050 GHG-Step
North Central Coast (NCC)	Monterey	**75**	**72**	64	12	3	0
	San Benito	**97**	**75**	65	44	31	0
	Santa Cruz	**81**	**72**	67	17	15	0
South Coast (SC)	Los Angeles	**95**	69	**70**	45	0	3
	Orange	**92**	63	**70**	43	0	4
	Riverside	**123**	**80**	**79**	62	47	43
	San Bernardino	**121**	**80**	**82**	63	45	49
South Central Coast (SCC)	Ventura	**83**	66	63	46	0	0
San Diego (SD)	San Diego	**93**	68	67	48	1	2
San Francisco (SF)	Alameda	**65**	65	65	1	0	0
	Contra Costa	**73**	67	64	14	0	0
	Marin	**70**	65	64	2	0	0
	Napa	**78**	72	63	20	4	0
	San Francisco	52	53	63	0	0	0
	San Mateo	45	56	61	0	0	0
	Santa Clara	69	68	67	3	2	1
	Solano	**82**	**71**	64	36	10	0
	Sonoma	**74**	66	58	7	0	0
San Joaquin Valley (SJV)	Fresno	**98**	**70**	63	50	3	0
	Kern	**111**	68	60	66	1	0
	Kings	**103**	68	61	57	2	0
	Merced	**98**	**71**	63	59	5	0
	San Joaquin	**95**	**72**	65	55	13	0
	Stanislaus	**100**	**71**	65	63	7	0
	Tulare	**112**	**71**	62	70	6	0
Sacramento Valley (SV)	Sacramento	**100**	**75**	64	59	22	0
California (CA)	Statewide	**87**	66	66	42	0	0

Almost half (10 of 23) of the counties exceeding the O_3 NAAQS in 2010 would achieve attainment of the standards in the 2050 BAU scenario and nearly all (19 out of 23) counties would achieve attainment under the 2050 GHG-Step scenario. Only the SC counties of Los Angeles, Orange, Riverside, and San Bernardino are predicted to remain out of attainment of the ozone NAAQS in the 2050 GHG-Step scenario.

As noted above, some regions experience ozone disbenefits under the GHG-Step scenario, which has implications for compliance with the ozone NAAQS. Table 1 illustrates that increases in the fourth highest 8 h ozone concentrations under the GHG-Step scenario may prevent Orange and Los Angeles counties from complying with the 70 ppb standard. The fourth highest 8 h ozone concentrations in San Bernardino County would not comply with the O_3 NAAQS under either emissions scenario, with concentrations increasing from 80 ppb in the BAU scenario to 82 ppb in the GHG-Step scenario. Both San Francisco and San Mateo counties were predicted to experience higher ozone concentrations in the GHG-Step scenario but would remain in compliance, with maximum concentrations of 63 and 61 ppb, respectively.

Figure 4 illustrates the number of days exceeding the 8 h ozone standard of 70 ppb in California under 2010 conditions, the 2050 BAU scenario, and the 2050 GHG-Step scenario. Most counties in central California have ∼ 60 ozone exceedance days in 2010, ∼ 5–10 ozone exceedance days in the 2050 BAU scenario, and zero ozone exceedance days in the 2050 GHG-Step scenario. North Central Coast (NCC) basin ozone reductions in Monterey, San Benito, and Santa Cruz counties also enabled those counties to comply with the O_3 standards in the GHG-Step scenario. The relatively

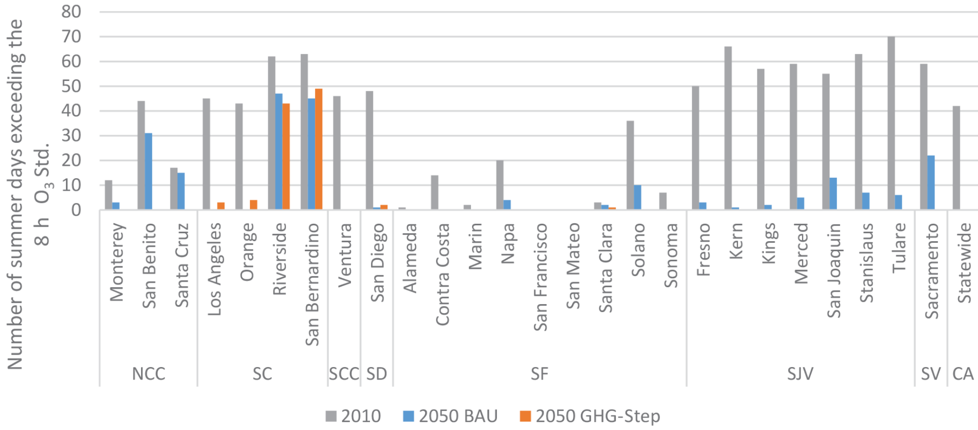

Figure 4. Number of days in the months of June–August 2054 in which the county population-weighted daily maximum 8 h average ozone concentration exceeds the 8 h ozone NAAQS of 70 ppb for each current and future year scenario.

small increase in ozone exceedance days in southern California counties like Los Angeles, Orange, San Bernardino, and San Diego will require extra mitigation strategies to achieve compliance with the ozone NAAQS.

3.2 $PM_{2.5}$ mass concentration

$PM_{2.5}$ concentrations can be analyzed on timescales ranging from seconds to years, but annual-average $PM_{2.5}$ concentrations are most commonly used to calculate mortality and health damages. Figure 5 illustrates annual-average $PM_{2.5}$ concentrations in northern-central California and southern California in 2054 under the BAU scenario (Fig. 5a) and the differences induced by the GHG-Step scenario (Fig. 5b). Both results use identical 2054 meteorology, ensuring that the concentration differences reflect changes between each scenario's emissions inventory. The highest BAU annual-average $PM_{2.5}$ concentration in southern California is $\sim 18\,\mu g\,m^{-3}$ in the city of San Bernardino located east of Los Angeles, with the next highest $PM_{2.5}$ hot spots occurring at San Diego and near the busy Port of Los Angeles and Long Beach. In Northern California, the annual-average $PM_{2.5}$ peaks at $25.3\,\mu g\,m^{-3}$ between the cities of Oakland and SF. Maximum $PM_{2.5}$ reductions in the GHG-Step scenario (Fig. 5b) occur between Oakland and SF ($-6\,\mu g\,m^{-3}$), in SD county ($-5.3\,\mu g\,m^{-3}$), and in San Bernardino county ($-3.5\,\mu g\,m^{-3}$). Overall, the reductions are significant (p value ≤ 0.1) over the majority of northern and southern California; the only non-significant $PM_{2.5}$ changes are two locations inland in northern Los Angeles around Lancaster and in midwestern San Bernardino, where BAU concentrations were low. Significant $PM_{2.5}$ increases of $+0.5\,\mu g\,m^{-3}$ do occur in ocean shipping routes because more fossil fuel is used for marine vessels in the GHG-Step scenario than in the BAU scenario. The GHG-Step scenario requires increased biofuel use as part of the overall strategy to reduce GHG emissions. This increased biofuel production is associated with higher biofuel costs since the least expensive biofuel feedstocks are used first followed by progressively more expensive feedstocks. As biofuel utilization increases, the demand and cost for conventional fossil fuels decreases. The decreased cost for fossil fuels in the GHG-Step scenario makes these fuels attractive for use by marine sources.

Population-weighted $PM_{2.5}$ concentrations (Fig. 2b) decrease for all regions in all seasons under the 2050 GHG-Step scenario relative to the BAU scenario. Variability in $PM_{2.5}$ concentrations is highest during the winter, with periods of intense stagnation intermixed with periods of vigorous atmospheric mixing. $PM_{2.5}$ concentrations are less variable in the summer months as demonstrated by the smaller IQR in Fig. 2b. The annual population-weighted $PM_{2.5}$ concentration drops from 6.0 to $4.8\,\mu g\,m^{-3}$ ($-20\,\%$) in the SJV, 8.3 to $6.2\,\mu g\,m^{-3}$ ($-25\,\%$) in SD, 9.5 to $7.8\,\mu g\,m^{-3}$ ($-18\,\%$) in SF, and 7.6 to $6.5\,\mu g\,m^{-3}$ ($-14\,\%$) for the SC air basin. Additional detail of the $PM_{2.5}$ species that decreases the most (e.g., nitrate) and the changes in the particulate size distribution are further described in the Supplement and summarized in Table S5.

Certain $PM_{2.5}$ spatial patterns illustrated in Fig. 5 were difficult to anticipate based exclusively on statewide emissions totals. For example, the $PM_{2.5}$ co-benefits from widespread adoption of new vehicle technology contribute significantly to statewide emissions reductions, but these changes were distributed over a larger area than the benefits associated with the decarbonization of freight modes (e.g., rail, aviation, and marine). Most on-road vehicles in California already have relatively low emissions rates for criteria pollutants. Further vehicular emissions savings result from small reductions that are distributed over the large number of vehicles across the entire state. This spreads the air quality improvements associated with vehicles over a large area. In contrast, freight modes use fuel with higher sulfur content burned in engines with less aftertreatment control (e.g., par-

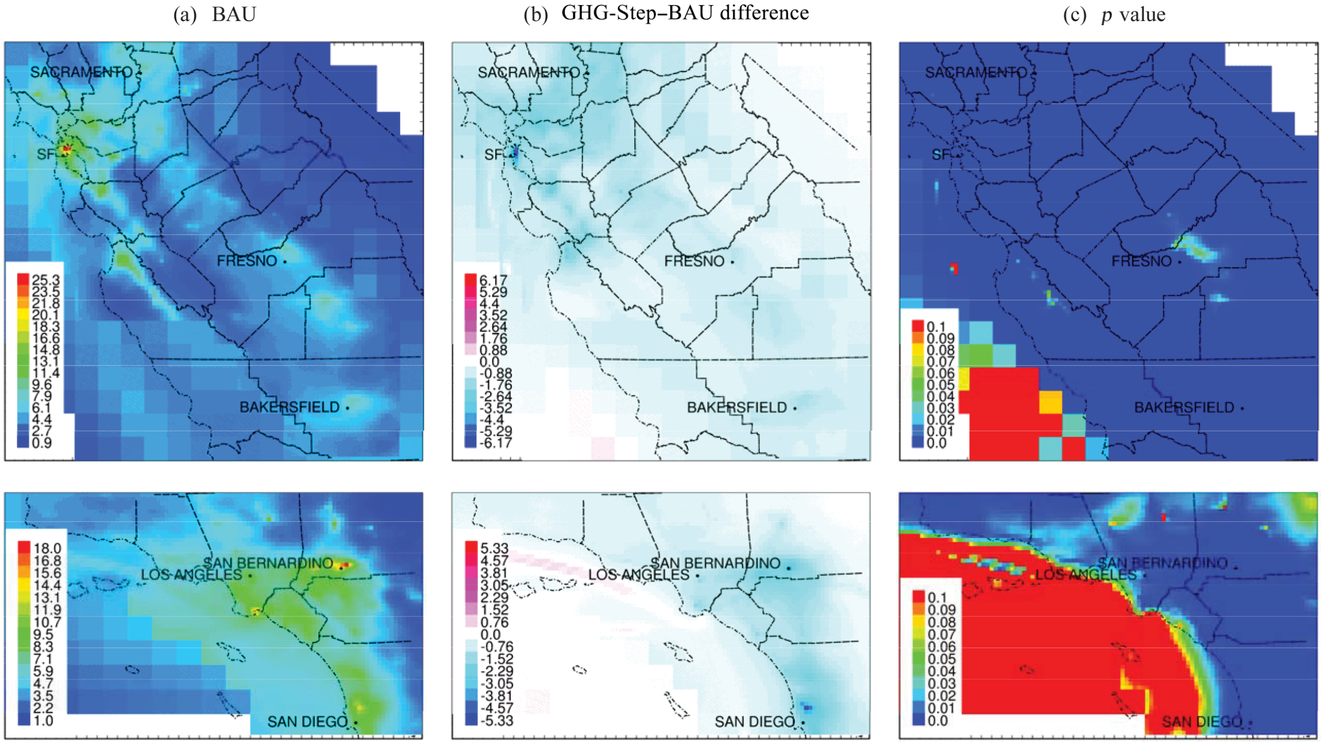

Figure 5. (a) Annual-average $PM_{2.5}$ mass concentration ($\mu g\,m^{-3}$) under the BAU scenario, **(b)** change in $PM_{2.5}$ mass concentrations ($\mu g\,m^{-3}$) under the GHG-Step scenario, and *p*-value significance level of the difference between concentrations predicted using the BAU and GHG-Step scenarios. All simulations for the year 2054. Both 24 km resolution results and the finer 4 km resolution results are shown, with the finer, smaller southern California or central-northern California domains overlaid upon the coarse California domain results.

ticulate filter) leading to higher particulate matter emission rates per energy consumed (e.g., $mg\,J^{-1}$). These sources are localized to goods movement corridors (shipping lanes, rail lines, etc.) that intersect at transport distribution hubs near ports. This leads to localized reductions in particulate matter concentrations associated with freight modes compared to more diffuse reductions associated with on-road sources. These trends were not obvious from statewide emissions tables but are clearly illustrated by the results from regional air quality modeling.

3.3 Associated $PM_{2.5}$ and O_3 mortality, mortality rate, and costs

Figures 6 and 7 illustrate the deaths, death rate, and cost associated with premature deaths from long-term annual exposure to both $PM_{2.5}$ and ozone (O_3).

3.3.1 Mortality

County and statewide $PM_{2.5}$- and O_3-associated deaths are displayed in Figs. 6a and 7a. The calculations summarized in Fig. 7a predict that 6400–10 600 people would die annually in the California 2050 BAU scenario due to exposure to $PM_{2.5}$ and O_3. The medium estimate for mortality falls between these low and high estimates. The range includes population growth through 2050. In the California GHG-Step scenario, total $PM_{2.5}$ and O_3 mortality would decrease to 4800–7900 deaths annually (24–26 % reduction) due to reductions in pollutant concentrations. More than 95 % of the premature mortality is associated with $PM_{2.5}$ while only 2.0–4.4 % is attributed to O_3. As a result, the O_3 increases associated with the GHG-Step scenario have a minor effect on mortality relative to $PM_{2.5}$. Spatial trends for $PM_{2.5}$ and O_3 mortality are similar, with the highest rates occurring in highly populated regions (see Figs. 3a and 5a). Likewise, most of the avoided mortality in the GHG-Step scenario also occurs in the regions with the highest populations.

3.3.2 Mortality rate

Air pollution mortality rates (deaths per 100 000 people) plotted in Figs. 6b and 7b help to compare health effects across urban and rural areas (both of which can experience high pollution events in California). The 2050 statewide air pollution mortality rate drops by 54–56 % in the 2050 GHG-Step scenario vs. the 2010 scenario and 24–26 % in the GHG-Step scenario vs. the BAU scenario. Reductions in the air pollution mortality rate were predicted in all counties under the GHG-Step scenario vs. the BAU scenario (Fig. 6b). In the 2050 BAU scenario, SF, San Mateo, Alameda, Contra Costa,

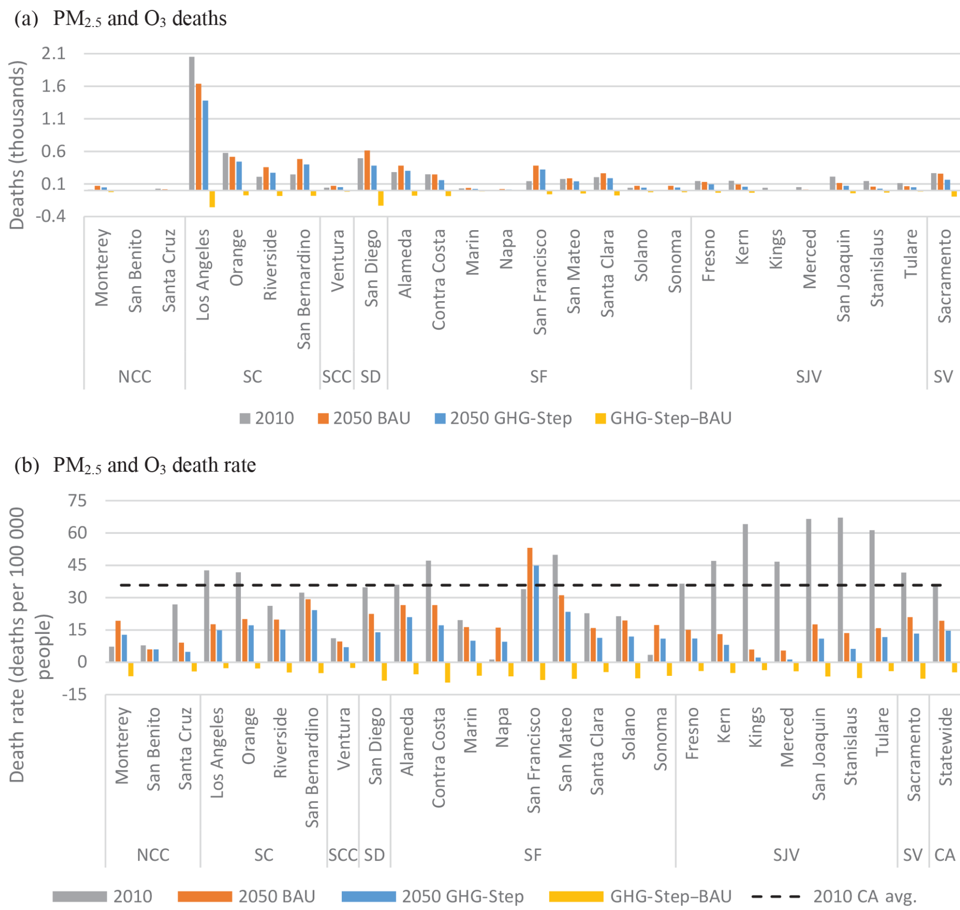

Figure 6. (a) $PM_{2.5}$ and O_3 long-term exposure deaths and **(b)** mortality rate by county, year, and emission scenario, based on combined Krewski et al. (2009) all-cause deaths associated with $PM_{2.5}$ risk ratio (RR) and Jerrett et al. (2009) respiratory deaths associated with ozone RR.

Sacramento, SD, and San Bernardino counties are predicted to have air pollution mortality rates higher than the statewide average of 19.3–32.2 deaths per 100 000 people (see Fig. 6b). Under the GHG-Step scenario, SF, San Mateo, and Alameda counties continue to have the highest death rates associated with $PM_{2.5}$ and O_3. Mortality rates in SF are more than double the statewide average due to the proximity of major construction projects and growing populations. Overall, Sacramento, Solano, Contra Costa, and SF counties are predicted to have the greatest reduction in $PM_{2.5}$ and O_3 mortality rates due to the adoption of GHG mitigation strategies. These patterns reflect a reduction in the emissions of criteria pollutants from construction projects but an increase in emissions from locations that produce new energy sources such as biofuels.

O_3 mortality is expected to increase from 260 deaths yr^{-1} in the BAU scenario to 490 deaths yr^{-1} in the GHG-Step scenario due to the increase in O_3 in key populated areas (mainly greater Los Angeles). The largest number of O_3-associated deaths ($\sim 25\,\%$) are estimated to occur in southern California due to the combination of high population and excess NO_x in the BAU scenario leading to increased O_3 concentrations when NO_x emissions decrease in the GHG-Step scenario. The portion of air pollution deaths due to O_3 would increase from 2.4 to 4 % in the BAU scenario to 6.2–10.1 % in the GHG-Step scenario, but overall mortality still decreases due to the overwhelming effect of $PM_{2.5}$ reductions.

3.4 Benefits

Using a VSL equal to USD 7.6 million per avoided death (Industrial Economics, 2011; Bart Ostro, personal communication, 2015), total costs for premature deaths in California equal $\sim$ USD 47.0–78.5 billion yr^{-1} in the 2050 BAU emissions scenario, with a savings of USD 11.4–20.4 billion yr^{-1} in the GHG-Step emissions scenario (right axis Fig. 7a). Los Angeles County has the highest premature mortality associated with air pollution (25 % of California) and thus the highest air pollution mortality cost under all emissions scenarios. Air pollution damages in Los Angeles County are valued at USD 15.2–25.5 billion yr^{-1} in 2010, which decreases to USD 12.1–19.6 billion yr^{-1} in 2050 BAU. Adoption of the GHG mitigation strategies in California re-

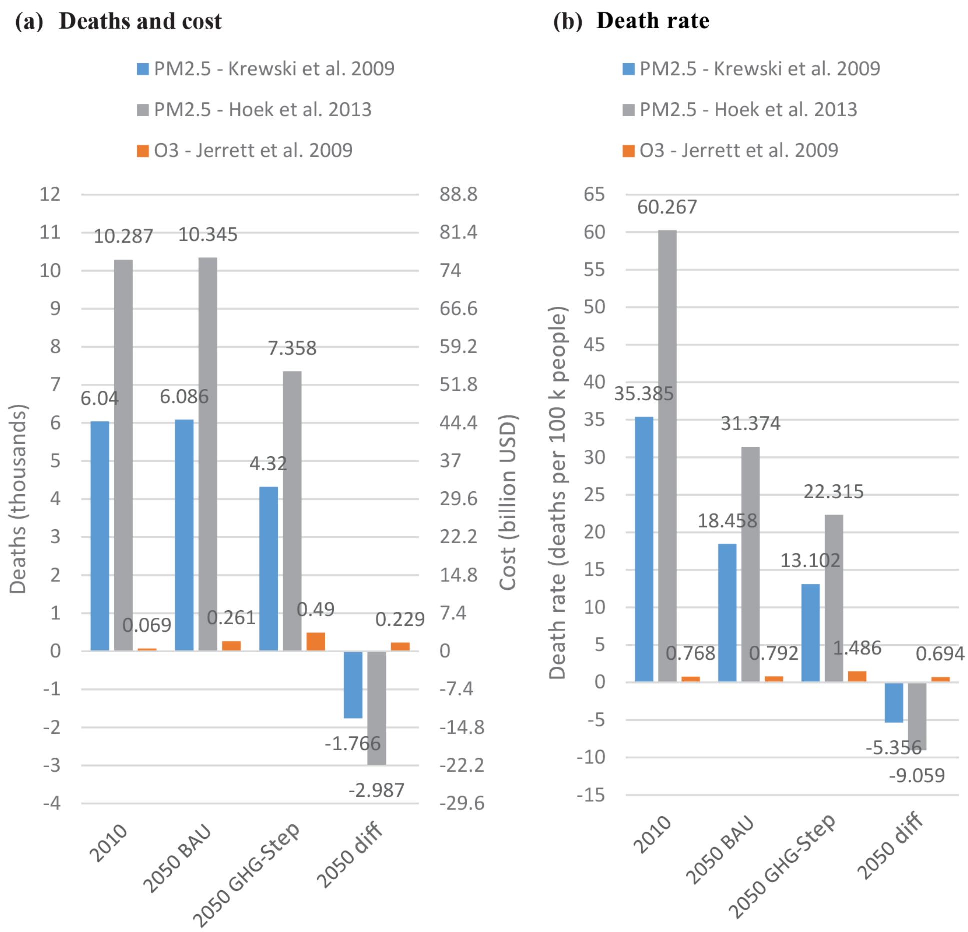

Figure 7. (a) Deaths and cost and **(b)** death rate for the high-resolution modeling domains covering 93 % of California's population. $PM_{2.5}$ damages are estimated using methods derived by Krewski et al. (2009) (blue bars) and Hoek et al. (2013) (gray bars). Ozone damages are estimated using the methods derived by Jerrett et al. (2009) (orange bars). Only bars with the same color should be compared between 2010, 2050 BAU, and 2050 GHG-Step. The "2050 Diff" category shows the difference between the 2050 GHG-Step and BAU scenarios.

duces air pollution damages in Los Angeles County by USD 1.9–3.6 billion yr^{-1} (17–18 % reduction). Other major counties also experience reduced air pollution costs under the GHG-Step scenario relative to BAU, including SD (USD 1.7–2.9 billion yr^{-1} reduction; 15 %–16 %) and Sacramento (USD 0.70–1.3 billion yr^{-1} reduction; 6.4 %). However, the largest cost savings per capita are predicted to occur in and around counties near SF based on the higher mortality rate reductions.

3.5 Implications

The costs for reducing California GHG emissions 80 % below 1990 levels by the year 2050 depend strongly on numerous assumptions about external factors such as the global price of oil. Only a few California energy models are available that attempt to calculate costs across the entire economy (Morrison et al., 2014, 2015). Analyses produced by the E3 PATHWAYS model (Williams et al., 2012; Energy+Environmental Economics (E3), 2015) suggest that meeting an intermediate target (40 % reduction in GHG emissions by the year 2030) using a non-optimized energy portfolio scenario would reduce personal income by USD 4.95 billion yr^{-1} (−0.15 %) and lower overall state gross domestic product by USD 16.1 billion yr^{-1} (−0.45 %). An analysis produced by the CA-TIMES model (Yang et al., 2014, 2015) indicates that the optimized GHG-Step scenario is *less* expensive than the BAU scenarios.

The air pollution analysis carried out in the current study predicts that the GHG-Step scenario will provide public health benefits equivalent to USD 11.4–20.4 billion yr^{-1} relative to the BAU scenario in 2050. The public health benefits described here have relatively tight uncertainty ranges with median values that are comparable to the more pessimistic of these two cost estimates for the adoption of low-carbon energy.

Figure 8 illustrates the public health savings associated with the GHG-Step scenario alongside the "fair-share" bene-

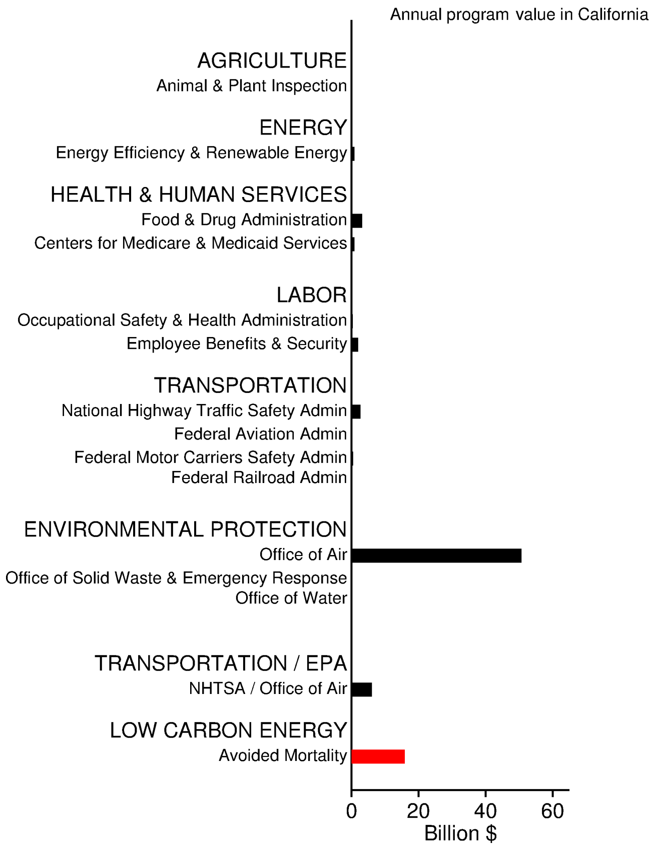

Figure 8. Annual "fair-share" benefits of federal programs that affect California in 2016. The fair-share fraction of US total is proportional to the fraction of US population living in California. "Low Carbon Energy" represents the difference between the 2050 GHG-Step–BAU scenarios calculated in the present study.

fits of federal programs (United States Office of Management and Budget, 2016) that affect California. Fair-share benefits are calculated using the fraction of US residents living in California multiplied by the total US benefits. The GHG-Step scenario yields benefits that are larger than those from of any program under the Federal Department of Agriculture, Energy, Health & Human Services, Labor, and Transportation. Only the National Ambient Air Quality Standards (NAAQS) under the US EPA have greater public health savings associated with reduced concentrations of air pollution. As shown throughout Sect. 3, strategies to reduce GHG emissions have benefits that overlap with NAAQS objectives and produce air quality improvements that would otherwise be challenging or impossible to achieve under the BAU scenario.

Taken together, the immediate and long-term savings associated with the GHG-Step scenario make a compelling case for the shift to a low-carbon energy system in California.

4 Conclusions

Measures to reduce GHG emissions to 80 % below 1990 levels in California under the GHG-Step scenario altered emissions of criteria pollutants (or their precursors) that generally brought nearly all regions of California into compliance with the O_3 NAAQS. A few of the dense urban areas experienced minor ozone disbenefits due to the effects of reduced NO_x concentrations leading to slightly higher ozone concentrations. Additional O_3 abatement strategies may be required to offset these minor effects, but the overall improvements in O_3 concentrations across the rest of the state appear to largely solve California's O_3 non-attainment problem. The nonlinear nature of the O_3 response to emissions changes emphasizes the need for the research community to include realistic chemical reaction models as a function of location in mitigation exercises.

The GHG-Step scenario reduced $PM_{2.5}$ concentrations across all regions of California through decreases in primary emissions and secondary formation pathways. $PM_{2.5}$ concentrations increased over ocean shipping lanes in the GHG-Step scenario but this has a negligible health impact. The inland $PM_{2.5}$ reductions drive the majority of the mortality reductions associated with the climate-friendly scenario. Total air pollution deaths in California decreased from 6400 to 10 600 per year in the 2050 BAU scenario to 4800–7900 per year in the GHG-Step scenario. These avoided deaths have a value of USD 12.2–20.5 billion yr^{-1} using a value of a statistical life equal to USD 7.6 million yr^{-1}. The avoided mortality benefits of low-carbon energy adoption in California exceed the present-day fair-share benefits of the combined programs under the Federal Department of Agriculture, Energy, Health & Human Services, Labor, and Transportation. Only the National Ambient Air Quality Standards (NAAQS) under the US EPA have greater public health benefits than adoption of low-carbon energy in California. These GHG measures and air quality programs complement and enhance one another, since adoption of low-carbon energy helps achieve compliance with the NAAQS that would otherwise be challenging or impossible to achieve under the BAU scenario. The public health benefits described here are comparable in value to published worst-case cost estimates for the adoption of low-carbon energy in California. Combined with other potential long-term benefits, these immediate health benefits strengthen the argument for the adoption of scenarios that reduce GHG emissions in California.

Data availability. The output concentration fields for the 2050 BAU and GHG-Step scenarios are available free of charge at https://faculty.engineering.ucdavis.edu/kleeman/

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Competing interests. The authors declare that they have no conflict of interest.

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