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$PM_{2.5}$ co-benefits of climate change legislation part 1: California's AB 32

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Abstract The Scoping Plan for compliance with California Assembly Bill 32 (Global Warming Solutions Act of 2006; AB 32) proposes a substantial reduction in 2020 greenhouse gas (GHG) emissions from all economic sectors through energy efficiency, renewable energy, and other technological measures. Most of the AB 32 Scoping Plan measures will simultaneously reduce emissions of traditional criteria pollutants along with GHGs leading to a co-benefit of improved air quality in California. The present study quantifies the airborne particulate matter ($PM_{2.5}$) co-benefits of AB 32 by comparing future air quality under a Business as Usual (BAU) scenario (without AB 32) to AB 32 implementation by sector. AB 32 measures were divided into five levels defined by sector as follows: 1) industrial sources, 2) electric utility and natural gas sources, 3) agricultural sources, 4) on-road mobile sources and 5) other mobile sources. Air quality throughout California was simulated using the UCD source-oriented air quality model during 12 days of severe air pollution and over 108 days of typical meteorology representing an annual average period in the year 2030 (10 years after the AB 32 adoption deadline). The net effect of all AB 32 measures reduced statewide primary PM and NO_x emissions by ~1 % and ~15 %, respectively. Air quality simulations predict that these emissions reductions lower population-weighted $PM_{2.5}$ concentrations by ~6 % for California. The South Coast Air Basin (SoCAB) experienced the greatest reductions in $PM_{2.5}$ concentrations due to the AB 32 transportation measures while the San Joaquin Valley (SJV) experiences the smallest reductions or even slight increases in $PM_{2.5}$ concentrations due to the AB 32 measures that called for increased use of dairy biogas for electricity generation. The ~6 % reduction in $PM_{2.5}$ exposure associated with AB 32 predicted in the current study reduced air pollution mortality in

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California by 6.2 %, avoiding 880 (560–1100) premature deaths per year for the conditions in 2030. The monetary benefit from this avoided mortality was estimated at \$5.4B/yr with a weighted average benefit of \$35 k/tonne (\$23 k/tonne–\$45 k/tonne) of PM, NO_x, SO_x, and NH_3 emissions reduction.

1 Introduction

The Intergovernmental Panel on Climate Change Fourth Assessment Report (Intergovernmental Panel on Climate Change 2007) identifies greenhouse gas (GHG) emissions as a strong contributing factor to climate change. California accounts for 0.53 % of the world's population but 1.6 % of the world's GHG emissions due to the high level of economic activity in the state. California Governor Arnold Schwarzenegger signed the Global Warming Solutions Act of 2006 (AB 32) mandating that California GHG emissions should return to 1990 levels by the year 2020 (Assembly Bill No. 32 Chapter 488 2006). Opponents of AB 32 argue that the law will hinder California's economy because the costs of compliance outweigh the benefits of climate change mitigation. This argument does not account for the co-benefits that AB 32 may provide through improved air quality due to a simultaneous reduction in traditional criteria pollutant emissions such as particulate matter (PM), oxides of nitrogen (NO_x), oxides of sulfur (SO_x), and reactive organic gases (ROGs). The potential for an air quality co-benefit is significant since California currently experiences some of the highest air pollution concentrations in the United States.

Quantifying the potential air quality co-benefits of AB 32 is a complex undertaking because atmospheric chemistry is inherently non-linear. A decrease in NO_x emissions reduces the formation of secondary PM at low NO_x/ROG ratios but increases the formation of secondary PM at high NO_x/ROG ratios. The emissions changes associated with AB 32 may therefore not produce proportional reductions in $PM_{2.5}$ concentrations. A full analysis with a chemical transport model is necessary to understand the impact of AB 32 on population exposure to $PM_{2.5}$. Previous studies suggest that air quality benefits associated with climate change mitigation policies may be appreciable (Nemet et al. 2010). Reduced air pollution exposure due to GHG mitigation measures can avoid up to 13,000 premature deaths per million population (Wilkinson et al. 2009; Woodcock et al. 2009; Markandya et al. 2009; Friel et al. 2009; Smith et al. 2009; Haines et al. 2009) leading to substantial economic benefits that can compensate for GHG mitigation costs (Bollen et al. 2009; Netherlands Environmental Assessment Agency 2009). Predicted air quality and health co-benefits vary substantially depending on the mitigation approach and the application regions.

The purpose of the present study is to quantify how AB 32 could impact ground level concentrations of airborne particulate matter with aerodynamic diameter less than 2.5 μm ($PM_{2.5}$) in California. The measures outlined in the AB 32 Scoping Plan (California Air Resources Board 2008d) are analyzed to determine associated changes in criteria pollutant emissions during the year 2030, 10 years after the 2020 target year for full AB 32 implementation. The effects of AB 32 measures on different criteria pollutant emissions and ambient $PM_{2.5}$ concentrations are analyzed during an extreme 12-day SJV stagnation episode and over a time period representative of an annual average. These analysis periods were selected based on 7 years of General Circulation Model predictions downscaled using regional climate models (Zhao et al. 2011a, b; Mahmud et al. 2010). The effects of AB 32 measures on $PM_{2.5}$ mass and $PM_{2.5}$ nitrate, sulfate, elemental and organic carbon concentrations are quantified over the entire state of California using a regional air quality model that accounts for atmospheric transformation. The potential public health implications are then inferred from population-weighted concentrations combined with mortality estimates derived from epidemiological studies. Part 2 of this study will examine the air pollution co-benefits from the transportation sector of California Governor's Executive Order S-3-05 which calls for an 80 % reduction in GHG emissions, relative to 1990, by the year 2050.

2 Methods

2.1 Determination of criteria pollutant emissions changes associated with AB 32

AB 32 contains numerous measures to reduce greenhouse gas emissions that span multiple economic sectors (California Air Resources Board 2008b, 2010a). Criteria pollutant emissions scaling factors for each measure were calculated based on Environmental Impact Reports and/or energy consumption reports. Criteria pollutant emission changes not defined by AB 32 were obtained from supplemental information sources such as US EPA and/or these criteria pollutant emission scaling thresholds were set based on practical limits of market adoption as discussed in the following sections. Emissions control levels were taken directly from AB 32 or inferred from energy efficiency improvements. When ranges for emissions reductions or efficiency improvements were given in the reports referenced, the average value within the range was used. This assumption generates ≤0.2 % uncertainty in the statewide emissions for each of the criteria pollutants.

AB 32 measures were organized into five categories based on economic sector or sub-sector (see Table 1). These categories have been described in this study as "implementation levels" because they were applied in a cumulative fashion (each implementation level builds on effects of previous levels; see Figs. 1 and 2) to quantify how controls for each sector contribute to $PM_{2.5}$ reduction. The cumulative total of all implementation levels is the total emission or air quality impact of AB 32 from all sectors. Note that AB 32 does not define implementation levels and this method of organization is used only to provide greater understanding of the underlying relationships between AB 32 and $PM_{2.5}$ concentrations in California. A summary of the BAU emissions and the emission changes associated with each implementation level is shown in Table 2. A more detailed summary of the emissions changes associated with individual AB 32 measures is provided in Supplemental Information.

2.1.1 Emission changes from industrial sources—Implementation Level 1

AB 32 Implementation Level 1 includes control measures that reduce GHG emissions from large industrial facilities. The measures incorporated into Level 1 include energy efficiency audits, refinery flare recovery, natural gas distribution improvements, and increased use of composting to generate biogas for electricity generation. Industrial point sources that emit >0.5 $MMTCO_2e$ per year such as oil and gas extraction, hydrogen plants, and mineral plants were affected by the energy efficiency audits measure (California Air Resources Board 2009c). All refineries and cement production plants were included in the energy efficiency audits measure even if they emitted <0.5 MMTCO2e because these industries were identified as extremely energy intensive in the AB 32 Scoping Plan. Energy efficiency improvements stemming from the audits were assumed to reduce energy consumption for cement plants (6.25 %), refineries (15 %), and all other facilities (10 %) with equivalent reductions in criteria pollutant emissions (Worrell and Galitsky 2005, 2008; Coito et al. 2005; Xenergy Inc. 2001). Several of these values represent the average of bounding estimates for possible efficiency improvements; see the discussion of sensitivity analysis associated with Table 2. Other Scoping Plan measures targeted the oil and gas industrial processes that emit methane and CO_2 such as oil and gas

Table 1 Categorization of AB 32 measures into five cumulative levels. Cumulative refers to the inclusion of all measures incorporated in previous economic sector implementation levels (see Fig. 2). Not all AB 32 Scoping Plan measures are shown here; only measures considered by this study

Label	Emission sector	Selected key measures	Emission source description
Level 1	Industrial	• Energy efficiency audits • Refinery flare recovery • Natural gas transmission and distribution GHG reduction • Landfill methane control	• Refineries • Cement manufacturers • Oil & gas extraction • Hydrogen manufacturing plant • Mineral plant • Landfill methane control
Level 2	Electric utility & residential and commercial natural gas	• Renewable electricity standard • Energy efficiency • Increase combined heat & power • Natural gas efficiency • Solar roofs • Solar water heating • Green buildings • Water use efficiency, reuse, recycling	• Electric utilities (buildings) • Residential natural gas usage • Commercial buildings consuming natural gas • Wastewater treatment facilities
Level 3	Agricultural	• Methane capture on large dairies	• Large dairy facilities
Level 4	On-road mobile	• Low carbon fuel standard • Pavley I, II—GHG Standards (LDV) • Aerodynamic efficiency (HDV) • Tire inflation (LDV) • Vehicle hybridization (MDV, HDV) • Port drayage trucks (HDV)—emission standard	• Light duty vehicles (passenger) • Medium duty vehicles (commercial) • Heavy duty vehicles (goods movement)
Level 5	Other mobile	• Ship electrification at ports • Transportation refrigeration unit plug in • Vessel speed reduction • Clean (green) ships	• Ocean going vessels • Commercial harbor craft • Cargo handling equipment • Transportation refrigeration unit • Freight rail • Commercial aircraft

extraction, transmission, distribution, flare recovery and removal of methane exemption at refineries (California Air Resources Board 2008a). Together CO_2 and CH_4 make only minor direct contributions to urban and regional particulate air pollution concentrations in California and so these specific measures have little impact on the results in the current study. Implementation Level 1 also includes commercial and industrial waste management measures from the AB 32 Scoping Plan such as methane control at landfills. The landfill gas recoverable for electricity generation has the potential to increase current landfill gas energy production by 36 % (Environmental Protection Agency 2011; R.W. Beck Inc. & Cascadia Consulting Group 2006) hence reducing commercial, institutional and government solid waste landfill TOG emissions, but offsetting less than 1 % of the state's electricity generation. All emissions

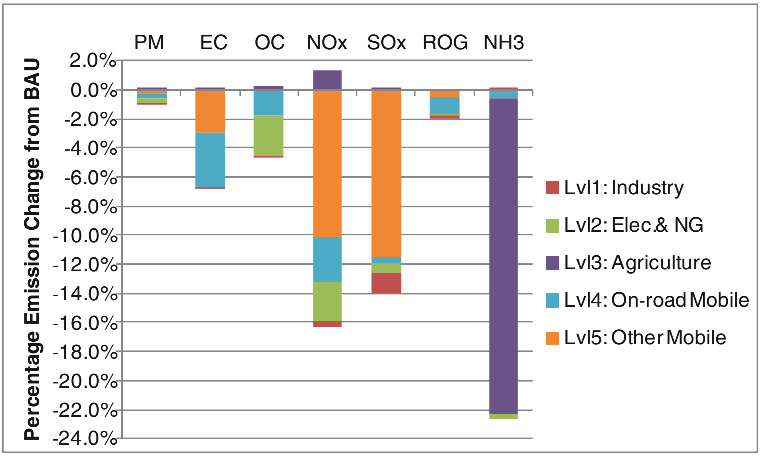

Fig. 1 Reductions or increases caused by each AB 32 implementation level for total particulate matter mass (PM), particulate elemental carbon (EC), particulate organic carbon (OC), oxides of nitrogen (NO_x), oxides of sulfur (SO_x), reactive organic gases (ROG), and ammonia (NH_3)

associated with electrical generation from biogas were represented using the appropriate chemical profiles for these facilities with emissions rates scaled by total electrical output.

2.1.2 Emission changes from electrical generation and natural gas sources—Implementation Level 2

AB 32 Implementation Level 2 defined in this study applies to traditional utilities (electricity and natural gas). The effects of measures that impact the consumption and generation of electricity from traditional power plants were adjusted to recognize that California imports ~33 % of its electricity demand from out-of-state generation (California Energy Commission 2009). As a result, the decreases in electricity consumption forecasted for 2030 mitigated electricity generation for both in-state and out-of-state sources. The current study assumed that the relative portfolio of fossil fuel and renewable energy generation for in-state and out-

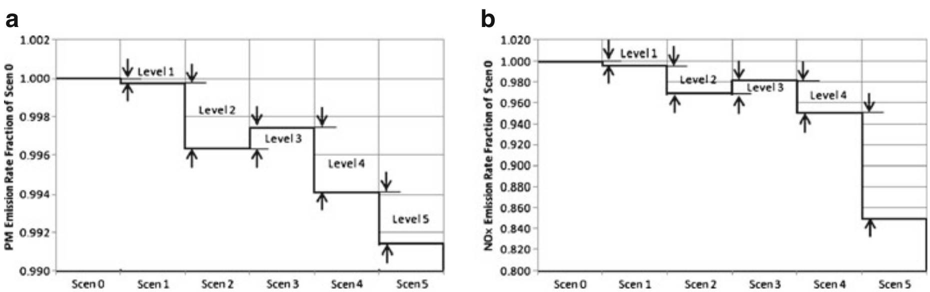

Fig. 2 Relative change in emissions rates caused by each cumulative AB 32 implementation level for **a** PM and **b** NO_x, where "Scen 0" is the BAU scenario. The difference between implementation levels is the change in emissions from the sources in that category. Levels 1–5 correspond to 1) industrial, 2) electric utility and natural gas, 3) agricultural, 4) on-road mobile, and 5) other mobile emission sources. Each "scenario" or model simulation is the cumulative of each additional level of emission reductions. Levels 2 and 3 are linked since part of the electrical generation capacity is shifted to methane combustion systems on large dairies

Table 2 Statewide 2030 daily average $PM_{2.5}$ emission rates and changes to emissions associated with AB 32. Uncertainty estimates in column three reflect the results of a sensitivity analysis conducted using the high and low estimates for control levels (where available)

		Emission rate change					
	BAU	All AB 32 Levels	Level 1—Industry	Level 2—Elec. & NG	Level 3—Agriculture	Level 4—On-road mobile	Level 5—Other mobile
Mass kg/day (%)	2.35E+06	−2.0E+04	−5.9E+02	−8.0E+03	2.6E+03	−7.9E+03	−6.5E+03
		(−0.86±0.01 %)	(0.025 %)	(−0.34 %)	(0.11 %)	(−0.33 %)	(−0.27 %)
EC kg/day (%)	3.20E+04	−2.1E+03	−7.3E+00	−5.0E+00	5.5E+01	−1.2E+03	−9.3E+02
		(−6.6±0.03 %)	(−0.023 %)	(−0.016 %)	(0.17 %)	(−3.8 %)	(−2.9 %)
OC kg/day (%)	2.40E+05	−1.1E+04	−3.8E+02	−6.8E+03	5.9E+02	−4.0E+03	−1.9E+02
		(−4.5±0.14 %)	(−0.16 %)	(−2.8 %)	(0.25 %)	(−1.7 %)	(−0.077 %)
NO_x kmol/day (%)	3.82E+04	−5.7E+03	−1.5E+02	−1.0E+03	4.9E+02	−1.2E+03	−3.8E+03
		(−15±0.00 %)	(−0.40 %)	(−2.7 %)	(1.3 %)	(−3.1 %)	(−10.%)
SO_x kmol/day (%)	7.89E+03	−1.1E+03	−1.2E+02	−4.7E+01	1.0E+0	−3.2E+01	−9.1E+02
		(−14±0.03 %)	(−1.5 %)	(−0.60 %)	(0.013 %)	(−0.4 %)	(−12 %)
ROG kmol/day (%)	3.31E+04	−6.6E+02	−5.5E+01	−3.5E+01	−2.0+E0	−4.1E+02	−1.5E+02
		(−2.0±0.01 %)	(−0.17 %)	(−0.11 %)	(−0.0060 %)	(−1.3 %)	(−0.45 %)
NH_3 kmol/day (%)	3.89E+04	−8.8E+03	1.0E+00	−1.3E+02	−8.4E+03	−2.5E+02	0.0E+00
		(−23±0.01 %)	(0.0026 %)	(−0.32 %)	(−22 %)	(−0.64 %)	(0.0 %)

of-state sources would remain at 2008 levels in the absence of AB 32. The expected electricity consumption changes for all AB 32 measures were then first applied to fossil fuel sources, thus eliminating coal and natural gas electricity generation out of state (leaving large hydro, renewable, and nuclear out-of-state imports), followed by elimination of in-state coal and petroleum electricity generation, and reduction of in-state natural gas electricity generation (in rank order of preference).

The measures included in Level 2 broadly cover residential and commercial natural gas consumption associated with appliances (Kavalec and Gorin 2009; Flex Your Power 2007) and building construction and retrofits that have improved energy efficiency standards, solar water heating (California Air Resources Board 2008b), and overall reduced water consumption leading to lower water heating needs (American Gas Association 2011; Klein 2005). Specific measures within the Level 2 category include: (1) "greening" of new and existing schools, state, residential, and commercial buildings, (2) water recycling, runoff reuse, and efficiency measures, and (3) the Renewable Portfolio Standard (RPS) and million solar roofs initiative. Measures to "green" buildings were applied to both existing and new buildings. New green buildings were assumed to adopt building standards that reduced energy consumption by 6.8 % and appliance standards that reduced energy consumption by 8.8 % (California Energy Commission 2009; Kavalec and Gorin 2009). Energy efficiency retrofits of existing buildings was assumed to reduce average building energy consumption by 7.5 % (California Energy Commission 2005, Kavalec and Gorin 2009). Green buildings led to the largest reduction in electricity demand from the electricity measures. Water conservation measures reduced the energy associated with the transport, distribution, and treatment of water (Klein 2005). The specific measures included in the AB 32 Scoping Plan address water use and system efficiency (Gleick et al. 2005; California Water Resources Control Board 2008), recycling (California Department of Water Resources 2003), and runoff reuse (Garrison et al. 2009) translating to a 5.2 % reduction in electrical consumption associated with water use in California. Energy efficiency goals reduced annual electrical demand in the state of California by 32,000 GWh (8 %) with equivalent reductions in criteria pollutant emissions in the year 2030 (California Air Resources Board 2008d). The installation of 4GW of combined heat and power units to utilize waste heat for electricity generation displaced 30,000 GWh of electricity generated from fossil fuel combustion in the year 2030 (California Air Resources Board 2008c).

The Renewable Portfolio Standard (RPS) aims to increase the use of renewable energy sources for electricity generation from 12 % in 2010 to 33 % by 2030. Renewable electricity generation can be accomplished by technologies with essentially no criteria pollutant emissions such as wind, solar photovoltaic, and small hydropower. Emissions from solar thermal, and geothermal electricity generation were increased in proportion to the change in energy generation from each technology (California Air Resources Board 2010b). Renewable electricity generation also includes combusting fuels that emit criteria pollutants such as solid fuel biomass, landfill gas, and anaerobic digester gas. The combined effect of the RPS measure increased criteria pollutant emissions from renewable sources within California (California Air Resources Board 2010c). The net effect of all the measures contained within the Level 2 category defined in the current study reduced in-state electricity generation from fossil fuels (Electric Power Group L, and Consortium of Electric Reliability Technology Solutions 2004; California Energy Commission 2009) and increased electricity generation from renewable fuels, leading to reduced emissions for all criteria pollutants except PM.

2.1.3 Emission changes from agricultural sources—Implementation Level 3

Under Implementation Level 3 in the current study, “large dairies” were retrofitted with anaerobic digesters for methane capture and electricity generation. Large dairies were not explicitly defined by AB 32, but the US EPA defines a large dairy to be ≥500 dairy cows per facility (United States Environmental Protection Agency 2004). Over 1,000 dairy farms in California have ≥500 dairy cows, accounting for over 90 % (1.67 million) of all CA dairy cows in 2007 (United States Department of Agriculture 2009). Adoption of biogas digesters on all of these dairy farms was considered to be prohibitively expensive. In the current study, “large dairies” were defined as those with projected emissions of total organic gases (TOG) >5,100 kg/h in the year 2029. A total of 16 dairies meeting this criteria were assumed to install plug flow anaerobic digesters (Western United Resource Development Inc. 2009) yielding a total electrical generation capacity of 54.8 MW. Each digester was assumed to produce an average of 0.166 kW/ft^3 of methane combusted with no flaring. All digester units were further assumed to incorporate H_2S scrubbing to meet the SCAQMD criteria of 40ppmv H_2S in the emissions to prevent corrosion of the exhaust system and to prevent formation of sulfate aerosol in the atmosphere. The CO, NO_x, VOC, and PM emissions from each digester were specified at the level described by the SJV Best Available Control Technology (BACT) per MWh (San Joaquin Valley Unified Air Pollution Control District 2009). Ammonia emissions were reduced substantially since ammonia was combusted with the biogas rather than released into the atmosphere directly from the dairy waste. Based on work by Shaw and colleagues (Shaw et al. 2007), most of the VOC emissions from dairy cows are produced by animal respiration and enteric fermentation, and therefore the TOG area emissions were reduced by only 1 % due to dairy waste anaerobic digestion.

2.1.4 Emission changes from on-road mobile sources—Implementation Level 4

All AB 32 measures that reduced on-road vehicle emissions through use of alternative transportation modes, reduced energy intensity, or altered the fuel mix were incorporated into Implementation Level 4 in the current study. For example, High Speed Rail (HSR) was assumed to reduce highway travel (California High Speed Rail Authority and Federal Railroad Administration 2005) and thus criteria pollutant emissions from on-road gasoline engines. Transportation mode shifts associated with HSR were based on the calculated reduction of vehicle miles traveled (VMT) and air travel for city-to-city trips (California High Speed Rail Authority and Federal Railroad Administration 2005). Energy intensity was decreased through the Pavley measures I and II (California Air Resources Board 2007a, 2008b), which call for increased efficiency through higher average fuel economy for the passenger fleet (California Air Resources Board 2008a, e). Energy intensity was also decreased by the tire tread and inflation program for light duty vehicles, reduced fuel consumption through hybridization of commercial vehicles, and assumed aerodynamic efficiency gains for heavy duty vehicles. Fuel mixtures were affected by the Low Carbon Fuel Standard (LCFS) (California Air Resources Board 2009b), which increased the production of alternative ethanol and biodiesel fuel feedstock while incorporating biofuels and compressed natural gas into the fuels for the light duty vehicle fleet. Fuel mixtures were also affected by increased market penetration of Zero Emission Vehicles (ZEV) powered by electricity and hydrogen fuel cells. It was assumed that 0.330 million (0.33 M) ZEVs would be driven on California roads by 2030 in accordance with the 2020 LCFS target (California Air Resources Board 2009b). The LCFS further assumes the penetration of other advanced technologies or emerging vehicles into the marketplace by the year 2020, including battery electric (0.22 M vehicles), plug-in hybrid electric (0.67 M vehicles), and fuel cell (0.11 M vehicles). It is forecasted that there will be 38.95 M vehicles registered in California by 2030 (California Department of Transportation Division of Transportation System Information 2009) and therefore ZEVs would account for ~1 % of the total fleet while other advanced technologies would account for 2.6 % of the total vehicle fleet. Diesel vehicles were influenced by additional measures related to goods movement. Specifically, drayage trucks operating within 80 miles of the Ports of San Diego, Long Beach, Los Angeles, Hueneme, Oakland, and San Francisco were required to install diesel particulate filters (DPFs) or otherwise meet the 2007 tailpipe emissions standards for heavy duty diesel vehicles (California Air Resources Board 2007b, 2010a). The regional goods movement system-wide efficiency goal was assumed to target heavy duty diesel vehicle emissions within ports (California Air Resources Board 2008a). Additional measures that applied to diesel vehicles included improvements to heavy duty aerodynamic efficiency and transport of alternative fuel feedstock through diesel trucks. The mobile fleet emission factors for PM and NO_x were based on default MOBILE6 factors which include Tier 2 standards when projected to 2030. SCR controls were not included in this analysis.

2.1.5 Emission changes from other mobile sources—Implementation Level 5

Implementation Level 5 includes measures that affect emissions from non-road modes of transportation such as air, water, rail, or off-road. The Goods Movement Emission Reduction Plan (GMERP) describes measures that were originally designed for reducing criteria pollutants related to international trade and the flow of goods (California Air Resources Board 2006a). Although its original purpose was to reduce adverse health impacts in the communities near ports, some of the measures in the GMERP were also incorporated in the Scoping Plan due to the fuel conservation and efficiency approaches that lead to CO_2 emission reductions. The LCFS calls for transport of alternative fuels by rail leading to increased emissions from locomotives (California Air Resources Board 2009b). HSR was also assumed to decrease the number of airplane trips within California (California High Speed Rail Authority and Federal Railroad Administration 2005) but slightly increased electrical demand. Cargo handling equipment was assumed to reduce idling and undergo hybridization and electrification (California Air Resources Board 2006b). Transport Refrigeration Units (TRUs) were assumed to be off when not in transit (California Air Resources Board 2008b). Several goods movement measures reduce emissions from ocean-going vessels or harbor craft. Cleaner ships that employed efficient engine designs, regular engine maintenance, fuel efficient steering through a vessel speed reduction near land, and even electrification at ports greatly reduced criteria pollutant emissions from ships (California Air Resources Board 2006a). Construction equipment and generators were not included in the other mobile source category since these sources were not addressed by AB 32.

2.2 Air quality modeling

Raw emissions inventories were based on the statewide inventory produced by the California Air Resources Board (CARB) projected for the year 2029 under compliance of the statewide implementation plan (SIP). The on-road mobile emissions inventory for the South Coast Air Basin (SoCAB) was provided by the South Coast Air Quality Management District (SCAQMD) for San Diego, Imperial, San Bernardino, Riverside, Los Angeles, and Orange counties. All other stationary, mobile, and area-wide emissions in the SoCAB were represented using the CARB statewide emissions inventory.

The CARB statewide raw emissions inventory had a spatial resolution of 4×4 km on a Lambert Conformal projection of the earth's surface forming a grid with 190×190 cells. The SCAQMD raw emissions inventory had a spatial resolution of 5×5 km on a Universal Transverse Mercator (UTM) coordinate system. The SCAQMD emissions were mapped to the Lambert projection and all calculations were performed on this grid. Both emissions inventories had temporal profiles for individual sources to model seasonal and/or day-of-week variations in emissions rates. The SCAQMD on-road mobile emissions inventory had diurnal scaling to represent average daily traffic patterns. All on-road mobile emissions and biogenic emissions were adjusted for variations in temperature and humidity (Mahmud et al. 2010). Soil dust was treated as a primary area source emission. None of the AB 32 measures limit emissions of soil dust, and so this source was constant for all simulations. The raw emissions were processed with detailed gas composition profiles and PM size and composition profiles to create inputs for modeling. Emissions were processed in eight different categories corresponding to the AB 32 implementation categories: electric utility, residential and commercial natural gas, on-road gasoline mobile, on-road diesel, other mobile, industrial, agricultural, and other miscellaneous.

The future air pollution episodes used to evaluate the air quality impacts of AB 32 were identified by downscaling Global Circulation Model (GCM) results produced by the Parallel Climate Model (PCM) using the Weather Research and Forecasting (WRF) regional climate model for the years 2047–2053 (Mahmud et al. 2010). The stagnation episode predicted for January 1–16, 2050 was selected as the representative meteorological input conditions for a severe future air pollution episode observed in the SJV (Mahmud et al. 2010). Nine episodes lasting 16 days each distributed evenly through the year 2052 were selected as representative meteorological conditions for future annual averages (Mahmud et al. 2010). Previous studies show that the episodes are representative of the 7-year average future meteorology in California (Mahmud et al. 2010).

Both meteorological fields and processed emissions were provided as inputs into the UCD-CIT source-oriented 3D Eulerian photochemical airshed model. The UCD model represented PM using 15 logarithmically scaled size bins from 0.01 to 10.0 μm. Gas phase photochemical reactions were represented using the SAPRC90 chemical mechanism (Ying et al. 2007) and dynamic gas to particle conversion reactions were represented using the treatment described by Jacobson (Jacobson 2005). The vapor pressures of inorganic gases above each particle were calculated using a modified version of ISORROPIA (Nenes et al. 1998). An absorption model based on smog chamber experiments was used to predict secondary organic aerosol formation (Ying et al. 2007). Pollutant transport from sources outside California is generally minor since the prevailing wind condition during air pollution events is west to east with the Pacific Ocean on the upwind side of the simulation. Hemispheric background conditions over the Pacific Ocean were used to represent long range transport. The background concentrations used in the current study were based on conditions measured during the California Regional Particulate Air Quality Study (CRPAQS) as used in previous modeling exercises (Ying et al. 2008).

Air quality simulations were run at a resolution of 8×8 km for each 16 day simulation period. The four initial days were omitted from the final data analysis to reduce the influence of initial and boundary conditions. Six air quality simulations were run separately during the extreme stagnation period (Jan 2050) to account for the change in air pollution associated with each AB 32 implementation level. Together, this creates a "staircase" of emission changes, with each step representing a different cumulative level of AB 32 implementation (see Fig. 2). The final level represents the change of emissions from all AB 32 measures. Two air quality simulations were run over the annual average episodes to evaluate air quality under BAU conditions and under full adoption of all AB 32 measures.

3 Results

3.1 Business-as-usual $PM_{2.5}$ concentration during an extreme pollution event

Business as Usual (BAU) $PM_{2.5}$ mass concentrations were predicted to be highest near the cities of San Francisco, Los Angeles, Fresno and Stockton during the extreme stagnation episode. The maximum 12-day average $PM_{2.5}$ mass concentrations reach 25–30 μg m^{-3} at these locations with sharp spatial gradients around urban centers reflecting the signal from primary combustion sources in addition to the regional dust and ammonium nitrate signals. Predicted $PM_{2.5}$ mass concentrations reach 22 μg m^{-3} in Imperial county due to windblown dust. Sea salt aerosol from breaking waves accounted for approximately 10 μg m^{-3} over the ocean cells but only trace amounts of this material reaches inland locations. The major components of the particulate matter mass include elemental carbon (EC), organic carbon (OC), sulfate, nitrate, and ammonium ion. EC and OC are produced by primary combustion sources that are clustered in cities and along transportation corridors. Sulfate concentrations peak at the locations of maximum shipping activity around the ports of Los Angeles, San Francisco and Oakland and in offshore shipping lanes. The highest concentrations of EC, OC and sulfate occur in the port of San Francisco and Oakland. Ammonium nitrate concentrations are predicted to reach a maximum of approximately 7.3 μg m^{-3} in the SJV where emissions of ammonia from agricultural sources are highest.

3.2 Impact of AB 32 on $PM_{2.5}$ concentrations during an extreme pollution event

Figure 4 displays the change in $PM_{2.5}$ concentrations caused by various levels of AB 32 implementation during the simulated extreme pollution event. AB 32 defined Implementation Level 1 and 2 produced large $PM_{2.5}$ mass reductions at specific industrial and electric utility point sources with exceptionally high emission rates. Figure 3b and c show reductions of 1.8 μg m^{-3} $PM_{2.5}$ mass near Concord (industrial Level 1 controls) and reductions of 4.3 μg m^{-3} $PM_{2.5}$ mass near Salinas (electric utility and natural gas Level 2 controls) over the 8×8 km^2 or 16×16 km^2 area surrounding each facility. Regional effects from these point source controls are muted with changes <1 μg m^{-3}. The dairy manure digester and electricity generation implemented in the SJV under defined Implementation Level 3 causes an increase in $PM_{2.5}$ mass of about 1 μg m^{-3} mostly due to increased concentrations of secondary nitrate and sulfate (see Supp. Info.). These components draw more ammonium into the particle phase in the SJV resulting in reduced transport of ammonium to surrounding regions and therefore reduced ammonium nitrate concentrations in surrounding regions. AB 32 defined Implementation Level 4 reduces concentrations of $PM_{2.5}$ mass associated with on-road vehicles by a maximum amount of 0.7 μg m^{-3} in San Francisco and Los Angeles with lesser reductions in the SJV and regions of slight (~0.2 μg m^{-3}) increase in the foothills of the mountains surrounding the SJV. Reduced NO_x emissions in the SJV lead to reduced nitrate concentrations in the SJV which allows more ammonia to be transported to the surrounding regions where it can contribute to particulate ammonium nitrate formation. AB 32 defined Implementation Level 5 (other mobile AB 32 measures) reduces $PM_{2.5}$ concentrations by 5 μg m^{-3} in the areas immediately around the ports of Los Angeles and San Francisco due to decreases in EC and sulfate concentrations associated with shipping measures. Figure 4a summarizes that the net effect of all the AB 32 measures within Implementation Levels 1–5 will reduce $PM_{2.5}$ mass concentrations by ~2–3 μg m^{-3} over the major urban areas of California with peak reductions of 5.5 μg m^{-3} at the ports and around major point sources during the simulated

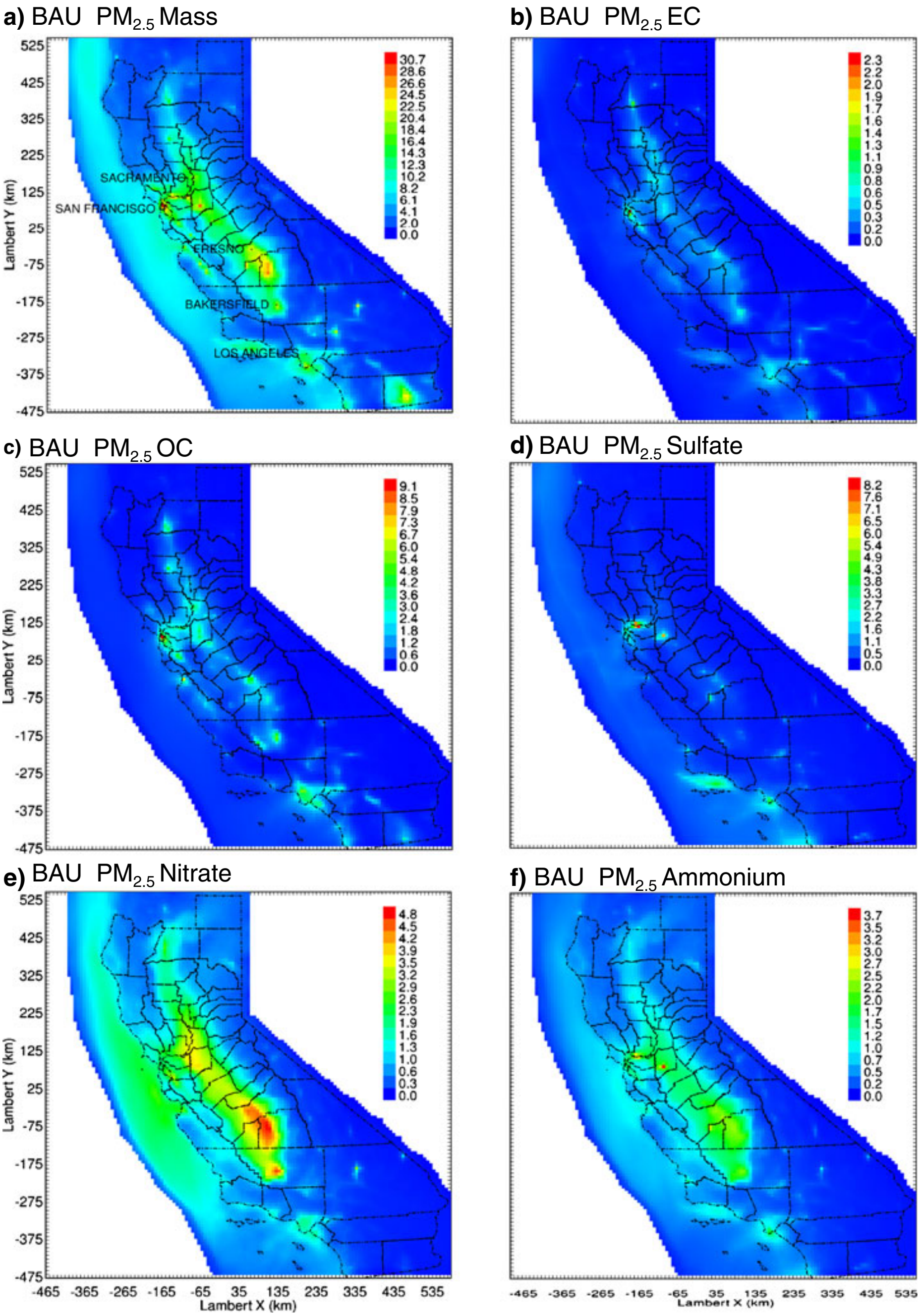

Fig. 3 Business as Usual (BAU) $PM_{2.5}$ concentrations (without AB 32 controls) during the January 2050 12-day severe winter stagnation event. $PM_{2.5}$ concentrations are shown for panel **a** total mass, and component contributions from **b** EC, **c** OC, **d** sulfate, **e** nitrate and **f** ammonium ion. All results are in μg m^{-3}

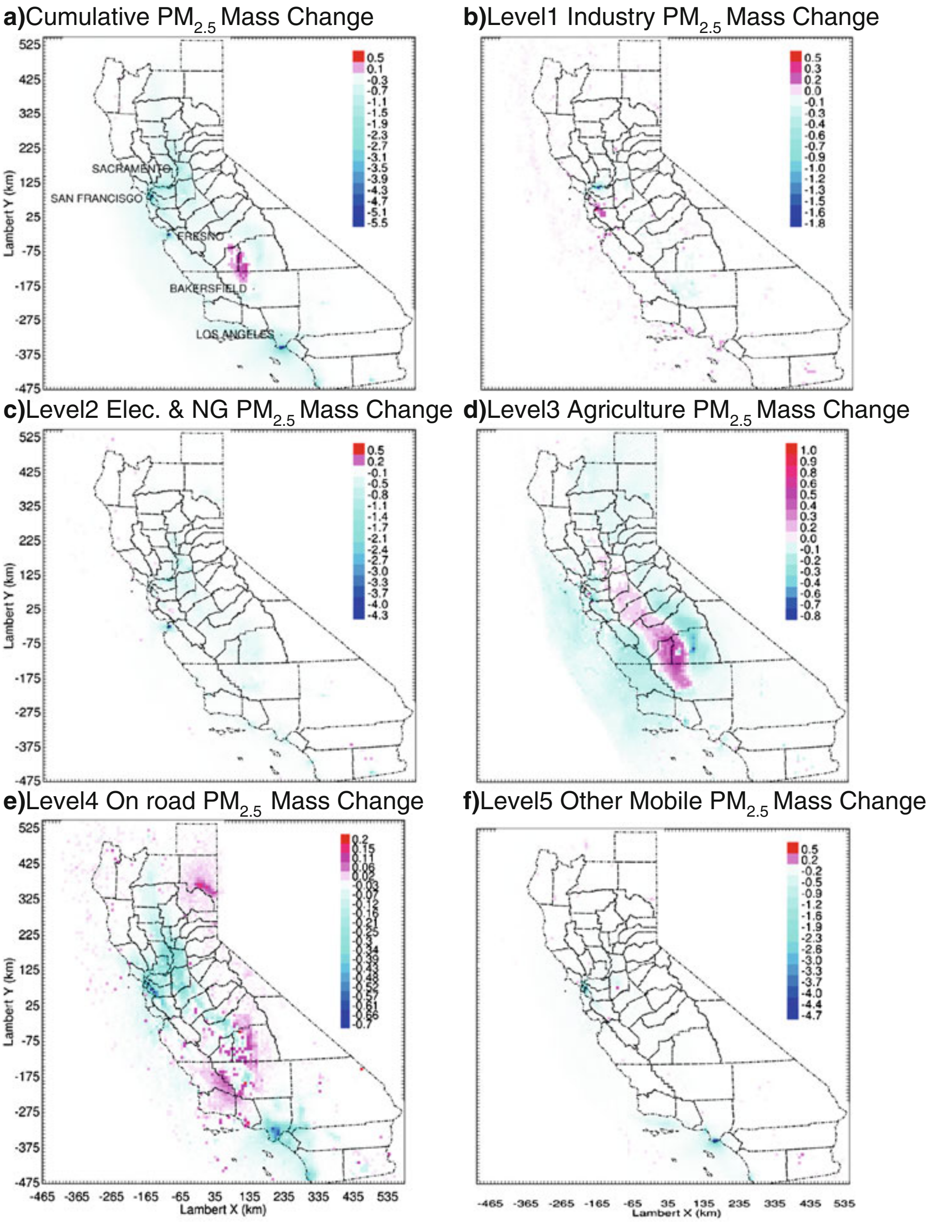

Fig. 4 Changes in $PM_{2.5}$ mass concentration ($\mu g\ m^{-3}$) for all defined AB 32 Implementation Levels for the January 2050 episode. Panel **a** illustrates cumulative effects of all Levels while panel **b**–**f** illustrate individual changes associated with each Level relative to the previous Level. *Red* indicates increased concentrations while *blue* indicates decreased concentrations. Please note that each panel has a different color scale and are not necessarily symmetric around zero

severe winter stagnation event. However, the addition of 54.8 MW of electrical generation capacity from dairy biogas digesters in the SJV leads to increased $PM_{2.5}$ mass concentrations of 0.3 μg m^{-3} at the location where the ammonia emissions are the highest.

3.3 Impact of AB 32 on population-weighted concentrations

Population weighted concentrations are a useful metric to evaluate the public health implications of policies that produce mixed outcomes for air pollution concentrations. Population weighted concentrations account for the spatial variability of the pollutant relative to the population so that different emissions control strategies can be compared. The population-weighted average concentration of $PM_{2.5}$ mass, EC, OC, sulfate, nitrate, and ammonium were calculated for the last 12 days of each 16 day simulation period. Results are summarized for the major air basins in California and for the state as a whole. California's population is projected to grow from 37.3 million in 2010 (United States Census Bureau 2011) to 49.2 million in 2030 (California Department of Finance 2007). The current study accounted for the projected population growth but the year 2000 spatial pattern of population density was used to maintain consistency with the assumptions inherent in the emissions inventory. All January 2050 episode results are expressed as the percent change relative to BAU for each Implementation Level. The variability of the daily average $PM_{2.5}$ concentration for the extreme pollution episode was used to calculate the 95 % confidence intervals bracketing the change in population-weighted concentrations using the student's t-distribution test with 11 degrees of freedom. The variability of the daily average $PM_{2.5}$ concentration for the 108 days simulated for 2052 is presented in Fig. 6 as a box and whisker plot.

Figure 5 illustrates that full implementation of AB 32 measures reduce population weighted $PM_{2.5}$ mass and component concentrations in California by ≥6 % during a severe air pollution episode. Measures within defined Implementation Levels 2, 4, and 5 (electricity generation and natural gas, on-road and other mobile sources) each produce approximately 2 % reductions in population weighted $PM_{2.5}$ concentrations with smaller savings achieved by Implementation levels 1 and 3 (industrial and agricultural sources). Each Implementation Level affects $PM_{2.5}$ component concentrations differently. Statewide population-weighted EC concentrations are affected most strongly by Implementation Levels 4 and 5 which target transportation sources, while OC concentrations are most strongly affected by Implementation Levels 2 which target electricity generation and Implementation Level 4. Population-weighted sulfate concentrations are most strongly affected by Implementation Level 5 while ammonium nitrate concentrations are most strongly affected by Implementation Levels 2 and 4.

Each air basin in California experiences a different response to AB 32 due to the variation of emission sources and activity levels for each region within the state. Generally speaking, the SoCAB experiences the greatest reduction in $PM_{2.5}$ mass and component concentrations due to AB 32 emissions control measures (Fig. 5d), while the SJV experiences the smallest reductions (or even slight increases for $PM_{2.5}$ sulfate) (Fig. 5c). The single strongest factor contributing to this increased $PM_{2.5}$ concentration trend in the SJV is the shift in electrical generation from combusting traditional fossil fuel outside the SJV to combusting renewable dairy biogas within the SJV. This AB 32 measure produces a clear GHG benefit for the state of California because it decreases bio-methane emissions into the atmosphere, but it worsens air quality for residents of the SJV. The NO_x produced by the dairy digester combustion systems contributes to increased ammonium nitrate concentrations in the SJV. Dairy biogas also contains trace amounts of sulfur (unlike natural gas) leading to increased SO_x emissions and sulfate formation even with the addition of substantial controls. The urban centers in the

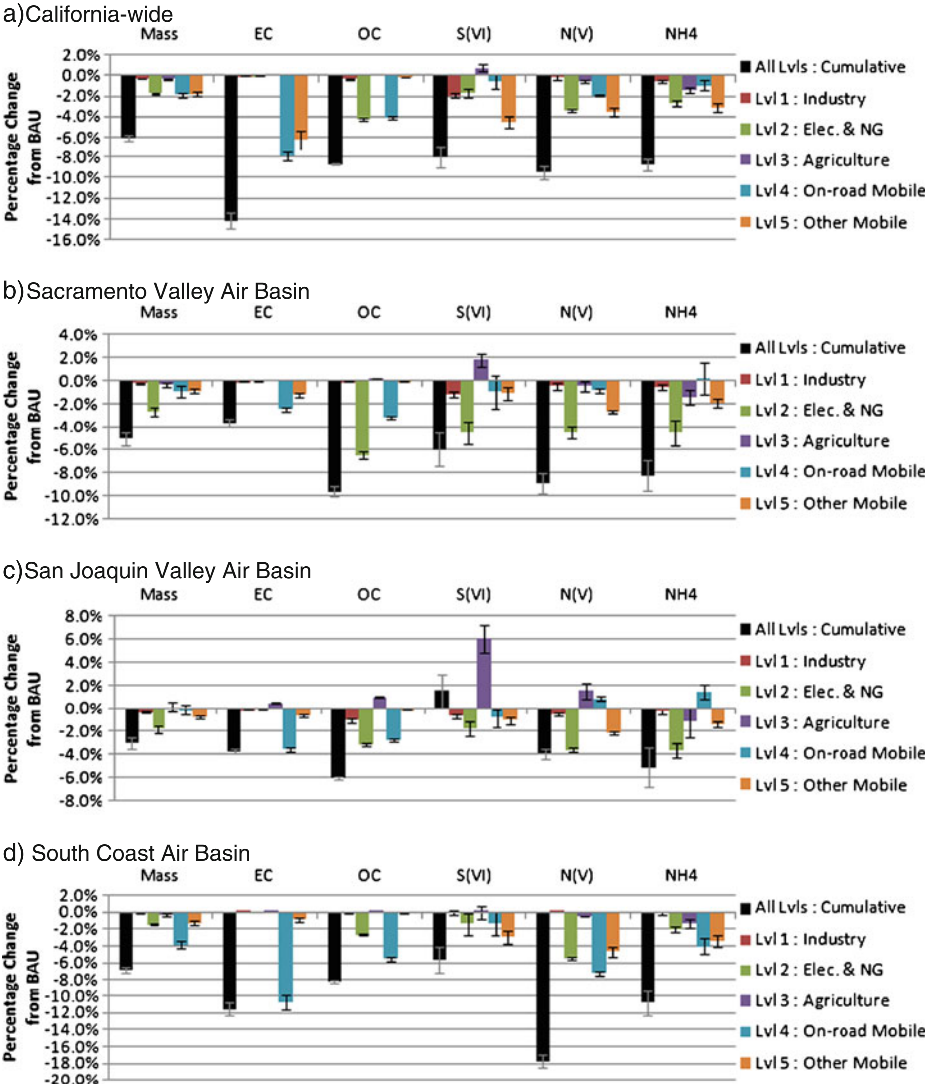

Fig. 5 Population weighted average change in $PM_{2.5}$ mass, EC, OC, sulfate (S(VI)), nitrate (N(V)), and ammonium (NH4) during the 12 day extreme stagnation episode

SoCAB benefit strongly from vehicular emission reductions and shipping measures at the port of Los Angeles.

The annual-average results (see Fig. 6) are generally consistent with the extreme event results (see Fig. 5). Annual-average population-weighted $PM_{2.5}$ concentrations decrease by statistically significant amounts ($p<0.05$) in each basin due to the adoption of AB 32. The statewide reduction in 24-h average $PM_{2.5}$ exposure has a median value of ~5–6 % with a maximum as large as 10 % and a minimum as small as 3 % depending on the exact meteorological conditions on a given day during the annual average period. $PM_{2.5}$ sulfate concentrations for the SJV experienced the least reduction and occasional increases with a median value of −0.7 %. Nitrate and ammonium exhibited the greatest sensitivity to daily

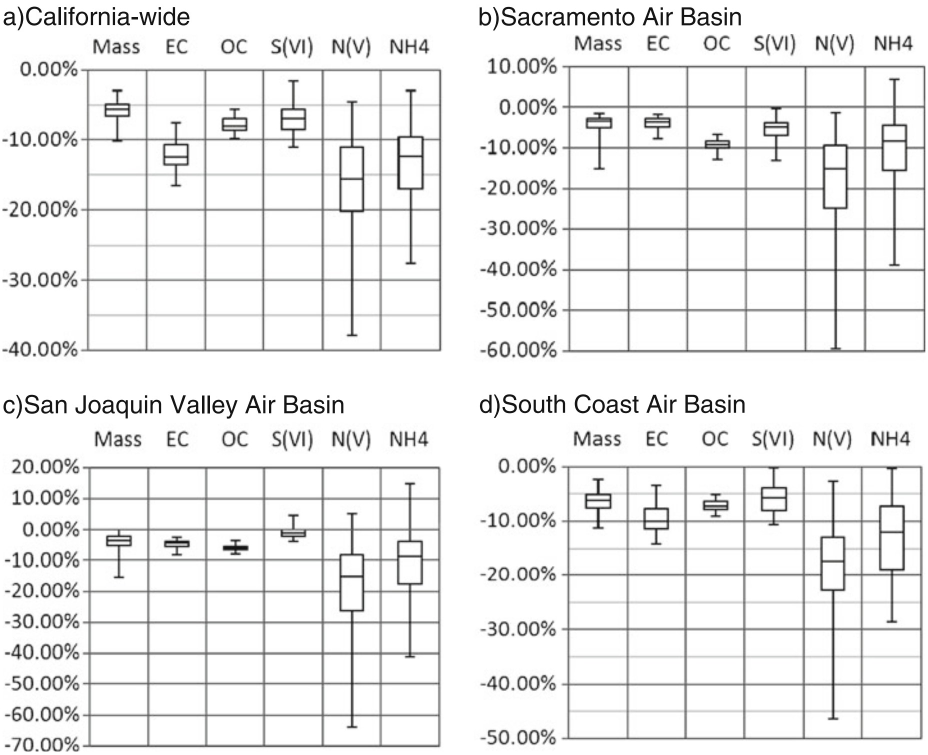

Fig. 6 Box and whisker plot of the minimum, 25th percentile, median, 75th percentile, and maximum change (%) in population weighted $PM_{2.5}$ concentrations caused by AB 32 over 108 days representing the annual average in 2052

variations in meteorology, with changes to statewide population exposure ranging from ~5–38 % and ~3–27 %, respectively. The SoCAB experienced higher annual average population-weighted $PM_{2.5}$ mass reductions of ~6 %, while SJV and Sacramento experienced reductions of ~3–4 % in response to AB 32.

3.4 AB 32 health benefits associated with reduced $PM_{2.5}$ concentrations

The change in mortality (ΔM) due to reduced exposure to $PM_{2.5}$ was calculated using Eq. (1):

$$\Delta M = \sum_{i=1}^{n} MP_i \left(1 - \frac{1}{\exp\left(\beta\, \Delta PM_{2.5,i}\right)} \right) \tag{1}$$

The change in mortality (ΔM) was determined using projected 2030 populations ages ≥30 years (P_i) (State of California Department of Finance 2007) for each 64 km^2 grid cell i in California. The change in $PM_{2.5}$ ($\Delta PM_{2.5}$) for each cell under the BAU scenario versus AB 32 scenario (all AB 32 measures incorporated) was quantified using the results from the 108 simulated days that are representative of the annual average meteorology. The basecase value of the risk factor β was taken to be approximately 0.01 (Roman et al. 2008). The basecase mortality rate, M, was set to 0.006343 for urban grid cells (≥500 people per square mile), or

0.009911 for rural grid cells (<500 people per square mile) (United States Department of Health and Human Services (US DHHS), Centers for Disease Control and Prevention (CDC), National Center for Health Statistics (NCHS) 2012). The uncertainty of the change in mortality predicted by Eq. 1 was calculated by using β of approximately 0.006 (Pope et al. 2002) and 0.012 (Laden et al. 2006) for the lower and upper uncertainty bounds. Further uncertainty in mortality estimates were quantified using the alternative method described by Jacobson (2010). This alternative approach used the same mortality rate for urban and rural locations (M=0.008097) and a range of risk factors (β_{low}=0.001, β_{medium}=0.004, β_{high}=0.008) when $PM_{2.5} \geq 8\ \mu g\ m^{-3}$. The value of β was divided by 4 when $PM_{2.5} < 8\ \mu g\ m^{-3}$. The change in mortality for all methods was expressed in monetary terms using the Value of a Statistical Life (VSL) approach (Viscusi and Aldy 2003).

Table 3 summarizes the results of health impact calculations. Equation (1) predicted that 880 premature deaths per year would be avoided in 2030 due to reduced $PM_{2.5}$ concentrations associated with the adoption of AB 32. The uncertainty range for this basecase estimate was 560–1,100 deaths per year. The annual average mortality from business-as-usual $PM_{2.5}$ exposure was estimated to be ~14,000 (9,100, 18,000) deaths per year in 2030. Hence, a reduction of ~880 (560, 1,100) deaths per year represents a 6.2 % reduction in the annual mortality caused by $PM_{2.5}$ in California. Assuming a VSL of $6.2 million, the estimated total monetary value of this AB 32 co-benefit was predicted to be $5.4B/yr ($3.5B/yr–$7.0B/yr). The alternative method for mortality estimation predicted an 11.5 % reduction in mortality due to the adoption of AB32 with an uncertainty range for associated costs that spanned the basecase estimate.

Fann et al. have previously estimated the health benefit of emissions control measures for the SJV in California (Fann et al. 2009). The emissions changes summarized in Table 2 of the current study combined with methodology described by Fann (accounting for the dose–response relationship summarized by Eq. 1) produced an estimated health benefit of approximately $44,500 per short ton (~$49 k per metric ton) of emissions reduction (averaged across all pollutants). The health benefits summarized in Table 3 ($5.44B/yr) combined with the emissions reductions summarized in Table 2 (~150,000 metric tons per year of PM, NO_x, SO_x, and NH_3) yielded a health benefit of $35 k ($23 k–$45 k) per metric ton of emissions reduction (averaged across all pollutants). The methods employed in the current study differ from the methods employed by Fann et al. due to the increased accuracy of the treatment for climate/meteorology, emissions, and air pollutant concentrations.

Table 3 Mortality incidence and cost valuation associated with AB 32 due to changes in $PM_{2.5}$. Method 1 incorporates Eq. 1, with urban and rural mortality rates, and β coefficients of 0.009355, 0.006, and 0.012 for the average, and lower and upper uncertainty range shown in *parenthesis*. Method 2 incorporates no specific urban or rural mortality rate, but uses a different low, medium, and high β coefficient for 0–8 $\mu g/m^3$ or greater than 8 $\mu g/m^3$. Intermediate calculations use full precision while final results are rounded to two significant figures for presentation

	Method 1: Equation 1 (this study)	Method 2: Jacobson (2010)
Mortality incidence from BAU $PM_{2.5}$ Exposure (deaths in hundreds)	140 (91, 180)	54 (14, 110)
Mortality change from AB 32 (deaths avoided in hundreds)	8.8 (5.6, 11)	6.2 (1.6, 12)
Total value from mortality change (billion US $)	5.4 (3.5, 7.0)	3.9 (0.99, 7.5)
Mortality cost value per metric ton PM, NOx, SOx, NH3 reduction (thousand US $/tonne)	35 (23, 45)	25 (6.4, 48)

4 Conclusions

California's Global Warming Solutions Act of 2006 (AB 32) is predicted to reduce population-weighted statewide $PM_{2.5}$ concentrations by ~6 %. Each California air basin experiences a unique response to AB 32 control measures due to the heterogeneous pattern of emission sources, previous control measures, and the new strategies adopted to reduce GHG emissions. The SoCAB experiences the greatest reductions in $PM_{2.5}$ concentrations due to transportation measures while the SJV experiences the smallest reductions or even slight increases in $PM_{2.5}$ concentrations mainly due to the increased use of dairy biogas for electricity generation in this region. GHG measures targeting transportation sources provide the largest co-benefits for $PM_{2.5}$ reduction in California. Transportation sources such as ships that previously were not subject to controls provide a strong opportunity to improve regional air quality while at the same time reducing GHG emissions. Energy efficiency measures are also beneficial to air quality, especially for cities with large point sources. Some renewable electricity generation strategies may increase air pollution concentrations even though they reduce statewide GHG emissions. In the present study, dairy methane capture and electricity generation measures in the SJV may increase population weighted concentrations of $PM_{2.5}$.

The ~6 % reduction in $PM_{2.5}$ exposure associated with AB 32 in the current study is predicted to reduce air pollution mortality in California by 6.2 %, avoiding 880 (560–1,120) premature deaths per year for the conditions in 2030. The monetary benefit from this avoided mortality is estimated at $5.4B/yr ($1B/yr–$7.5B/yr) with a weighted average benefit per tonne of $35 k/tonne ($23 k/tonne–$45 k/tonne) of PM, NO_x, SO_x, and NH_3 emissions reduction.

The measures in AB 32 are tailored to the opportunities in California given the high degree of pre-existing emissions controls as well as the use of clean fuels in the state. It is very likely that different states within the US or other nations around the globe that have less stringent controls for criteria pollutant emissions or very different energy portfolios (e.g. primarily coal) may have a much larger potential criteria pollutant co-benefits from the adoption of GHG emissions controls. Furthermore, alternative mitigation policies such as land use change may be more optimal and cost-effective in achieving integrated AQ and GHG goals for other regions in the world. The results of the current study should not be used to project the co-benefits of GHG mitigation outside of California.

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References

American Gas Association (2011) Annual statistics: appliance and housing data. http://www.aga.org/Kc/Research/statistics/annualstats/appliance/Pages/default.aspx. Accessed 27 Jan 2011

Assembly Bill No. 32 Chapter 488 (2006). Health and Safety Code, vol 25.5

Bollen J, Guay B, Jamet S, Corfee-Morlot J (2009) Co-benefits of climate change mitigation policies: literature review and new results. Economics Department Working Papers No. 693. Report No. ECO/WKP(2009)34. Organisation for Economic Co-operation and Development, Paris, France

California Air Resources Board (2006a) Emission reduction plan for ports and goods movement in California. California Air Resources Board, Sacramento, CA

California Air Resources Board (2006b) Proposed emission reduction plan for ports and goods movement in California. California Air Resources Board, Sacramento, CA

California Air Resources Board (2007a) Air Resources Board's proposed state strategy for California's 2007 State Implementation Plan: Appendix A. California Air Resources Board, Sacramento, CA
California Air Resources Board (2007b) Staff report: initial statement of reasons for proposed rulemaking. Proposed regulation for drayage trucks. California Air Resources Board, Sacramento, CA
California Air Resources Board (2008a) Climate change draft scoping plan: public health analysis supplement. Attachment A - Public health and environmental benefits of draft scoping plan measures. California Air Resources Board, Sacramento, CA
California Air Resources Board (2008b) Climate change scoping plan appendices: Volume I: supporting documents and measure detail, vol I. California Air Resources Board, Sacramento, CA
California Air Resources Board (2008c) Climate change scoping plan appendices: volume II: analysis and documentation, vol II. California Air Resources Board, Sacramento, CA
California Air Resources Board (2008d) Climate change scoping plan: a framework for change. Pursuant to AB 32 The California Global Warming Solutions Act of 2006. California Air Resources Board, Sacramento, CA
California Air Resources Board (2008e) Comparison of greenhouse gas reductions under CAFE standards and ARB regulations adopted persuant to AB1493. California Air Resources Board, Sacramento, CA
California Air Resources Board (2009a) Proposed regulation to implement the low carbon fuel standard: Vol I. Staff report: initial statement of reasons. California Air Resources Board, Sacramento, CA
California Air Resources Board (2009b) Proposed regulation to implement the low carbon fuel standard: Vol II. Appendices. California Air Resources Board, Sacramento, CA
California Air Resources Board (2009c) Public workshop to discuss proposed regulation for energy efficiency and co-benefits audits for large industrial facilities. Presentation. California Air Resources Board, Sacramento, CA
California Air Resources Board (2010a) Drayage truck regulation. California Air Resources Board, Sacramento, CA
California Air Resources Board (2010b) Scoping plan measures implementation timeline. California Air Resources Board, Sacramento, CA
California Air Resources Board (2010c) Status report: evaluation of environmental impacts of the renewable electricity standard. California Air Resources Board, Sacramento, CA
California Department of Finance (2007) Population projections for California and its counties 2000–2050, by age, gender and race/ethnicity. Sacramento, CA
California Department of Transportation Division of Transportation System Information (2009) 2008 California motor vehicle stock, travel, and fuel forecast. Sacramento, CA
California Department of Water Resources (2003) Water recycling 2030: recommendations of California's recycled water task force. California Department of Water Resources, Sacramento, CA
California Energy Commission (2005) Options for energy efficiency in existing buildings. Report No. CEC-400-2005-039-CMF. California Energy Commission, Sacramento, CA
California Energy Commission (2009) 2009 Integrated energy policy report. Report No. CEC-100-2009-003-CMF. California Energy Commission, Sacramento, CA
California High Speed Rail Authority and Federal Railroad Administration (2005) California high-speed train final program environmental impact report/environmental impact statement (EIR/EIS) for the proposed California high-speed train system volume I: report. Sacramento, CA and Washington, D.C.
California Water Resources Control Board (2008) Proposed WETCAT strategies and measures. Sacramento, CA
Coito F, Worrell E, Price L, Masanet E, Rufo M (2005) California industrial energy efficiency potential. In: DIVISION, E. E. T (ed) ACEEE 2005 summer study on energy efficiency in industry. ACEEE, Berkeley, pp 1–14
Electric Power Group L, and Consortium of Electric Reliability Technology Solutions (2004) California's electricity generation and transmission interconnection needs under alternative scenarios: assessment of resources, demand, need for transmission interconnections, policy issues and recommendations for long term transmission. Report No. 700-04-003. Contract No. 150-99-003. Prepared for California Energy Commission, Sacramento, CA by Electric Power Group, LLC and Consortium of Electric Reliability Technology Solutions
Environmental Protection Agency (2011) United States Environmental Protection Agency Interactive Conversion Tool. Landfill Methane Outreach Program. epa.gov/lmop/projects-candidates/interactive.html. Accessed 30 March 2010
Fann N, Fulcher CM, Hubbell BJ (2009) The influence of location, source, and emission type in estimates of the human health benefits of reducing a ton of air pollution. Air Qual Atmos Health 2:169–176
Flex Your Power (2007) Natural gas: collective annual savings [Online]. Available: www.fypower.org/res/naturalgas/calculations.html [Accessed]
Friel S, Dangour AD, Garnett T, Lock K, Chalabi Z, Roberts I, Butler A, Butler CD, Waage J, McMichael AJ, Haines A (2009) Health and Climate Change 4 Public health benefits of strategies to reduce greenhouse-gas emissions: food and agriculture. Lancet 374:2016–2025

Garrison N, Wilkinson RC, Horner R (2009) A clear blue future: how greening California cities can address water resources and climate challenges in the 21st century. National Resources Defense Council, New York, NY

Gleick PH, Cooley H, Groves D (2005) California water 2030: an efficient future. Report No EPA-430-B-97-015. Contract No. 68-D4-0088, GS-10F-0036K. Pacific Institute, Oakland, CA

Haines A, McMichael AJ, Smith KR, Roberts I, Woodcock J, Markandya A, Armstrong BG, Campbell-Lendrum D, Dangour AD, Davies M, Bruce N, Tonne C, Barrett M, Wilkinson P (2009) Health and Climate Change 6 Public health benefits of strategies to reduce greenhouse-gas emissions: overview and implications for policy makers. Lancet 374:2104–2114

Intergovernmental Panel on Climate Change (2007) Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdon and New York, NY, USA

Jacobson MZ (2005) A solution to the problem of nonequilibrium acid/base gas-particle transfer at long time step. Aerosol Sci Technol 39:92–103

Jacobson MZ (2010) Enhancement of local air pollution by urban CO2 domes. Environ Sci Technol 44:2497–2502

Kavalec C, Gorin T (2009) California energy demand 2010-2020, adopted forecast. Report No. CEC-200-2009-012-CMF. California Energy Comission, Sacramento, CA

Klein G (2005) California's water–energy relationship. Report No. CEC-700-2005-011-SF. California Energy Commission, Sacramento, CA

Laden F, Schwartz J, Speizer FE et al (2006) Reduction in fine particulate air pollution and mortality: extended follow-up of the Harvard Six Cities study. Am J Respir Crit Care Med 173:667–672

Mahmud A, Hixson M, Hu J, Zhao Z, Chen SH, Kleeman MJ (2010) Climate impact on airborne particulate matter concentrations in California using seven year analysis periods. Atmos Chem Phys 10:11097–11114

Markandya A, Armstrong BG, Hales S, Chiabai A, Criqui P, Mima S, Tonne C, Wilkinson P (2009) Health and climate change 3 Public health benefits of strategies to reduce greenhouse-gas emissions: low-carbon electricity generation. Lancet 374:2006–2015

Nemet GF, Holloway T, Meier P (2010) Implications of incorporating air-quality co-benefits into climate change policymaking. Environ Res Lett 5:014007

Nenes A, Pandis SN, Pilinis C (1998) ISORROPIA: a new thermodynamic equilibrium model for multiphase multicomponent inorganic aerosols. Aquat Geochem 4:123–152

Netherlands Environmental Assessment Agency (2009) Co-benefits of Climate Policy. Report # 500116005. In: Bollen J, Brink C, Eerens H, Manders T (eds) Netherlands Environmental Assessment Agency, Bilthoven, the Netherlands

Pope C, Burnett RT, Thun MJ et al (2002) Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. J Am Med Assoc 287:1132–1141

Roman HA, Walker KD, Walsh TL, Conner L, Richmond HM, Hubbell BJ, Kinney PL (2008) Expert judgment assessment of the mortality impact of changes in ambient fine particulate matter in the U.S. Environ Sci Technol 42:2268–2274

R.W. Beck Inc. and Cascadia Consulting Group (2006) Targeted statewide waste characterization study: characterization and quantification of residuals from materials recovery facilities. Report No. 341-06-005 Contract No. IWM-03027. Prepared for California Integrated Waste Management Board., Sacramento, CA, by R.W. Beck Inc. and Cascadia Consulting Group

San Joaquin Valley Unified Air Pollution Control District (2009) BACT Clearinghouse. Best Available Control Technology (BACT) Guideline 3.1.13. . 3.3.13 Waste Gas Fired IC Engine - > 50 hp. San Joaquin Valley Unified Air Pollution Control District, Modesto, CA

Shaw SL, Mitloehner FM, Jackson W, Depeters EJ, Fadel JG, Robinson PH, Holzinger R, Goldstein AH (2007) Volatile organic compound emissions from dairy cows and their waste as measured by proton-transfer-reaction mass spectrometry. Environ Sci Technol 41:1310–1316

Smith KR, Jerrett M, Anderson HR, Burnett RT, Stone V, Derwent R, Atkinson RW, Cohen A, Shonkoff SB, Krewski D, Pope CA III, Thun MJ, Thurston G (2009) Health and Climate Change 5 Public health benefits of strategies to reduce greenhouse-gas emissions: health implications of short-lived greenhouse pollutants. Lancet 374:2091–2103

United States Census Bureau (2011) 2010 Census Summary File 1: 2010 Census of Population and Housing. factfinder2.census.gov. Accessed 16 Dec 2011

United States Department of Agriculture (2009) 2007 Census of Agriculture: California State and County Data. vol 1. Report Number AC-07-A-5. USDA, Washington, D.C

United States Department of Health and Human Services (US DHHS), Centers for Disease Control and Prevention (CDC), National Center for Health Statistics (NCHS) (2012) Compressed Mortality File (CMF) on CDC WONDER Online Database. The current release for years 1999 - 2009 is compiled

from: CMF 1999-2009, Series 20, No. 2O, 2012. Centers for Disease Control and Prevention (CDC). http://wonder.cdc.gov/cmf-icd10.html. Accessed 23 Feb 2011
United States Environmental Protection Agency (2004) AgSTAR handbook: a manual for developing biogas systems at commercial farms in the United States. 2nd edn. United States Environmental Protection Agency, Washington, DC
Viscusi W, Aldy J (2003) The value of a statistical life: a critical review of market estimates throughout the world. J Risk Uncertain 27:5–76
Western United Resource Development Inc. (2009) Dairy power production program: dairy methane digester system program evaluation report. Report No. CEC-500-2009-009. Contract No. 400-01-001. Prepared for California Energy Comission, Sacramento, CA by Western United Resource Development Inc.
Wilkinson P, Smith KR, Davies M, Adair H, Armstrong BG, Barrett M, Bruce N, Haines A, Hamilton I, Oreszczyn T, Ridley I, Tonne C, Chalabi Z (2009) Health and Climate Change 1 Public health benefits of strategies to reduce greenhouse-gas emissions: household energy. Lancet 374:1917–1929
Woodcock J, Edwards P, Tonne C, Armstrong BG, Ashiru O, Banister D, Beevers S, Chalabi Z, Chowdhury Z, Cohen A, Franco OH, Haines A, Hickman R, Lindsay G, Mittal I, Mohan D, Tiwari G, Woodward A, Roberts I (2009) Health and Climate Change 2 Public health benefits of strategies to reduce greenhouse-gas emissions: urban land transport. Lancet 374:1917–1929
Worrell E, Galitsky C (2005) Energy efficiency improvement and cost saving opportunities for petroleum refineries. Report Number LBNL-56183. Contract No.DE-AC02-05CH11231. Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA
Worrell E, Galitsky C (2008) Energy efficiency improvement and cost saving opportunities for cement making. Report No. LBNL-54036-Revision. Contract No. DE-AC02-05CH11231. Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA
Xenergy Inc (2001) California industrial energy efficiency market characterization study. Pacific Gas and Electric Company, Oakland
Ying Q, Fraser MP, Griffin RJ, Chen JJ, Kleeman MJ (2007) Verification of a source-oriented externally mixed air quality model during a severe photochemical smog episode. Atmos Environ 41:1521–1538
Ying Q, Lu J, Allen P, Livingstone P, Kaduwela A, Kleeman M (2008) Modeling air quality during the California Regional PM10/PM2.5 Air Quality Study (CRPAQS) using the UCD/CIT source-oriented air quality model—part I. Base case model results. Atmos Environ 42:8954–8966
Zhao Z, Chen S-H, Kleeman MJ, Mahmud A (2011a) The impact of climate change on air quality–related meteorological conditions in California. Part II: present versus future time simulation analysis. Journal of Climate 24(13):3362–3376. doi:10.1175/2010jcli3850.1
Zhao Z, Chen S-H, Kleeman MJ, Tyree M, Cayan D (2011b) The impact of climate change on air quality–related meteorological conditions in California. Part I: present time simulation analysis. Journal of Climate 24(13):3344–3361. doi:10.1175/2011jcli3849.1