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Air quality impacts of implementing emission reduction strategies at southern California airports

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ABSTRACT

Reducing aviation emissions will be a major concern in the coming years, as the relative contribution of aviation to overall emissions is projected to increase in the future. The South Coast Air Basin of California (SoCAB) is an extreme nonattainment area with many airports located upwind of the most polluted regions in the basin. Techniques to reduce aviation emissions have been studied in the past, and strategies that can be implemented at airports include taxi-out times reduction, ground support equipment electrification and aviation biofuel implementation. These strategies have been analyzed only at the national scale, their effectiveness to improve air quality within the SoCAB given the local meteorology and chemical regimes is unclear. This work studies how the adoption of the techniques at commercial SoCAB airports affect ozone (O_3) and fine particulate matter ($PM_{2.5}$) concentrations. In addition, potential impacts on public exposure to $PM_{2.5}$ and O_3 resulting from changes in the concentration of these pollutants are estimated. In addition, the work calculates aviation emissions for each scenario and simulate the transport and atmospheric chemistry of the pollutants using the Community Multiscale Air Quality (CMAQ) model. The simultaneous application of all reduction strategies is projected to reduce the aviation-attributable population weighted ground-level $PM_{2.5}$ by 36% in summer and 32% in winter. On the other hand, O_3 increases by 16% in winter. Occurring mostly in densely populated areas, the decrease in ground-level $PM_{2.5}$ would have a positive health impact and help the region achieve attainment of national ambient air quality standards.

1. Introduction

1.1. Context

The South Coast Air Basin (SoCAB) of California is among the worst air quality regions in the United States (Razeghi et al., 2016), currently designated as an extreme nonattainment area (US EPA, 2017a). With global air transportation growing by 5% per year (Lee et al., 2009; Boeing, 2013; Kousoulidou et al., 2016) the relative contribution of aviation to overall emissions could increase from 3% to 15% by 2050 (Sgouridis et al., 2011). The SoCAB region contains several major US airports including the Los Angeles International Airport (LAX, the 3rd largest by passenger traffic), many of which are located upwind of the most polluted areas in SoCAB. Population exposure to poor air quality – i.e. elevated concentrations of fine partlbiculate matter (PM2.5) and ozone (O3) – has been linked with human health effects including premature mortality and morbidity (Shen et al., 2017). Airport operations are linked to mortality, and in the US alone they are estimated to cause ~350 early deaths in 2018 (Ashok et al., 2013). Under these constraints, it is beneficial to identify and assess strategies that minimize the relative impact of airports and air traffic on air quality in the SoCAB.

Previous studies have quantified the increase in criteria pollutant concentrations in the vicinity of SoCAB airport due to aircraft activity (Westerdahl et al., 2008; Shirmohammadi et al., 2017). Hudda et al. (2014) monitored particle number concentrations downwind of LAX and showed a 4-fold increase from background concentration levels. Other studies have quantified the health damages of SoCAB airports; Penn et al. (2017) estimated ~10 annual premature mortalities attributable to SoCAB airports emissions. Accounting for both climate and air quality, Nahlik et al. (2016) estimated ~210 million USD in annual damages attributable to SoCAB airports emissions in 2013.

The goal of this work is to assess the effects of mitigation strategies targeted at reducing the negative air quality of aviation emissions. It only considers strategies that are already gaining attention from airports, airlines, and regulatory agencies (e.g., the Federal Aviation Administration) and could be implemented feasibly in a reasonable time frame. Technologies such as electric commercial aircrafts are

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Fig. 1. (**a**) Computational domain for the WRF and CMAQ models. All subsequent plots encompass a subregion of the computational domain labeled as Plot region. (**b**) Location of the 5 SoCAB airports considered in this study (x marker): Los Angeles International Airport (LAX), John Wayne Airport (SNA), Ontario International Airport (ONT), Hollywood Burbank Airport (BUR), Long Beach Airport (LGB) and relevant cities (dot marker).

highly effective at reducing emissions but are out of the scope of this study due to a low technology readiness level. Therefore, well-documented and promising reduction strategies are selected and grouped into three categories according to their focus: (1) taxi-out time reduction, (2) ground support equipment electrification, and (3) implementation of alternative fuels.

1.2. Mitigation strategies

The taxi-out time is defined as the time between the aircraft push back from the gate and take off (Deonandan et al., 2010). Lowering taxi-out times reduces aircraft fuel burn, and previous works have achieved so through computer simulations (Balakrishnan and Jung, 2007; Lee and Balakrishnan, 2010) and field trials (Simaiakis et al., 2014). Currently, NASA is developing a next-generation interdisciplinary traffic management system that would minimize taxi-out times (Aponso et al., 2015). Deonandan et al. (2010) estimated that a 27% taxi-out emissions reduction can be achieved by applying queue management strategies at LAX. Also, Ashok et al. (2017) showed such strategies reduce air quality costs of taxi operations by ∼35% at the Detroit Metropolitan Airport. This strategy has the climate co-benefit of reducing CO_2 emissions, which are proportional to fuel burn.

Ground support equipment (GSE) contributed to 13% of overall NO_X emissions at airports in 2012 (ARB, 2016). US EPA (1999) demonstrated that it is technically possible to electrify all GSE while (ARB, 2011) showed that airports are currently interested in this concept. Regarding air quality, Yim et al. (2013) estimated that electrification of ground support equipment reduces by 28% the number of early deaths attributable to 2005 UK airport emissions. Also, this strategy offers the climate co-benefit of displacing diesel through partially renewable electricity.

Alternative aviation fuels general characteristics feature near-zero levels of sulfur and aromatic content which result in a 10-fold decrease in PM (Moore et al., 2015) and sulfur oxides emissions (Barrett et al., 2012), and a 5–10% reduction in NO_X and CO emissions (Lobo et al., 2012). For these reductions in gaseous emissions, alternative aviation fuels can reduce US landing and take-off health impacts by 26%, while the reduction in fine particle emissions would reduce air quality impacts by a further 11% (Ashok et al., 2013). Depending on their manufacturing pathway, alternative fuels are also climate beneficial by reducing life cycle GHG emissions. However, reducing sulfur emissions has the climate tradeoff of reducing negative radiative forcing (Kapadia et al., 2016). In 2016, LAX was the first American airport to use an alternative fuel (Bio-Derived Synthetic Paraffinic Kerosenes mixed with jet fuel) in commercial flights (United Airlines, 2013). These factors indicate that the SoCAB is a valuable target to study the airport attributable air quality impacts of widespread aviation biofuel adoption.

1.3. Purpose of paper

For the first time, this work quantifies the air quality impacts of three aviation emission reduction strategies applied at airports in the SoCAB area, with state-of-the-art air quality models. Each mitigation strategy is assessed independently, as well as the combined effects of simultaneously implementing all strategies, focusing on the impact on aviation emissions, air quality, and population exposure. Section 2 details the computation of aviation emission and the models used. Section 3 discusses the differences in emissions and population exposure between each scenario and the base case. Section 4 summarizes the effects of the studied environmental mitigation strategies on air quality, regulations, and health.

2. Methods

2.1. Emissions

In the United States Environmental Protection Agency (US EPA) available inventories, aircraft emissions are neither spatially resolved nor allocated by flight phase. Such level of detail is necessary to apply aviation mitigation strategies accurately. The Aviation Emissions Inventory Code (AEIC) developed by Stettler et al. (2011) and Stettler et al. (2013) is used to compute landing and takeoff (LTO) emissions (i.e., aircraft activity below 3000 ft) for each airport in the modeled domain (indicated in Fig. 1) as well as APUs and GSE emissions. The AEIC has been modified to model the studied mitigation strategies, the taxi-out time in mode and all emission indexes are multiplied by factors, which are described in section 2.2. The inventory developed in this work includes the LTO, APU and GSE emissions from the following airports: the Los Angeles International Airport (LAX), the John Wayne Airport (SNA), the Ontario International Airport (ONT), the Hollywood Burbank Airport (BUR), and the Long Beach Airport (LGB) for the year 2012. Emissions are spatially allocated in a rectangular grid of 400 m resolution and temporally resolved by hour. Please see the SI for further details and AEIC emission results.

Non-aviation anthropogenic emissions are based on the 2012 California Air Resources Board (ARB) inventory (ARB, 2016) and an updated Sparse Matrix Operator Kernel Emissions (SMOKE v4.0) (US EPA, 2017b). Biogenic emissions are obtained from the Model of Emissions of Gases and Aerosols from Nature (MEGAN) (Guenther et al., 2012).

2.2. Emission scenario development

Scenarios studied in this work represent the maximum achievable emissions reduction of the mitigation strategies they include, as described in Table 3, and therefore results represent the upper limit to the estimated impacts on air quality. The base case depicts the business-as-usual scenario, with no reductions in aircraft emissions, and is used to determine changes in air pollutant concentrations.

2.2.1. Taxi-out time reduction scenario

The taxi-out time reduction scenario (TOT) represents the upper-limit of airport surface traffic optimization strategies. Taxi-out emissions are proportional to its associated time in mode (TIM). The minimum taxi-out time of a flight is its unimpeded taxi-out time – i.e., when the aircraft does not encounter any congestion on the shortest taxi route from its gate to the runway. Using the data provided by the United States Federal Aviation Administration's (US FAA) Aviation System Performance Metrics (ASPM) database, the unimpeded taxi-out time was computed as the average taxi-out time minus the taxi-out time delay. It represents the theoretical maximum reduction in delays achievable through airport surface traffic management. The taxi-out time reduction scenario was implemented by coding the ratio between unimpeded taxi-out time and ASPM's average taxi-out time into the AEIC, where it multiplies the original taxi-out time of each flight.

2.2.2. Ground support equipment electrification scenario

The ground support equipment electrification scenario (GSE) excludes all emissions from GSE and APUs by considering that they are substituted with electrified sources. However, the base case includes GSE and APU emissions which are computed individually in the AEIC using default equipment assignments (Stettler et al., 2011). Additional power plant emissions due to the electrical grid load increase are not accounted for in the GSE scenario. Generally, air quality impacts of power consumption on the grid are much smaller than the air quality impacts of local combustion emissions to achieve equivalent power (Yim and Barrett, 2012).

2.2.3. Alternative aviation fuels implementation scenario

The alternative aviation fuels implementation scenario (BIO) represents the complete implementation of alternative aviation fuels in SoCAB airports. There are a number of viable and tested aviation biofuels that exist today. NASA and 11 other research groups collaborated on the Alternative Aviation Fuel Experiment (AAFEX I & AAFEX II) which tested three types of alternative fuels: Fischer-tropsch fuel synthesized from natural gas (FT1), from coal (FT2) as well as a tallow-based Hydroprocessed Renewable Jet (HRJ) (also called bio origin synthetic paraffinic kerosene, bio-SPK). The AAFEX study is the most extensive and detailed experimental set of tests of alternative aviation fuels available to date. Their results have been published in multiple peer-reviewed publications (Lobo et al., 2011, 2012; Santoni et al., 2011; Kinsey et al., 2012; Beyersdorf et al., 2014 Durdina et al., 2014; Brem et al., 2015; Moore et al., 2015). Experimental results from AAFEX I and II are used to scale Emission Indexes (EIs) of nitrogen oxides (NO_X), nitrous acid, sulfur oxides (SO_X), black carbon (BC) and organic carbon (OC) calculated by AEIC for both regular engines and APUs to model the emissions from FT1 fuel combustion. Among the studied fuels, FT1 is chosen as it is the most extensively detailed, but note that all three tested fuels exhibit similar emissions reductions relative to jet A-1 fuel. Aviation alternative biofuels show negligible reductions in CO and HC, a 5–10% reduction in NO_X at higher power conditions, SO_X emissions correlated with sulfur content, and large reductions in combustion-generated particles. The BIO scenario considers a 50/50 blend of FT1 and JP-8, consistent with the current FAA certification. By 2018, neat blends with 100% of biofuel content have not been proven as a feasible drop-in substitute, but the long-term goal is to fully replace jet A-1 fuel (U.S. Air Force, 2013). In the event that the FAA certification progresses, this study includes a scenario which considers 100% biofuels blends. Please refer to the SI for further details and results.

2.2.4. All combined scenario

The all combined scenario (ALL) implements the previous scenarios simultaneously to characterize their air quality benefits upper-bound. The non-linearity of atmospheric chemistry justifies the need for this scenario, as the scalar sum of the results of the previous three scenarios may not represent the maximum achievable air quality results.

2.3. Atmospheric modeling

The model used to perform simulations of atmospheric chemistry and transport is the Community Multi-scale Air Quality model (CMAQ) version 5.2, with the SAPRC07 chemical mechanism (Carter, 2010). CMAQ is a widely used state-of-the-art chemical transport model used in attainment demonstrations for National Ambient Air Quality Standards (NAAQS) for ozone (O_3) and fine particulate matter ($PM_{2.5}$) (Carreras-Sospedra et al., 2015). The modeling domain used in this study is illustrated in Fig. 1 and covers California using a 4 km × 4 km horizontal grid resolution in a 15-layer logarithmic vertical structure with a terrain-following sigma coordinate and a ceiling pressure of 100 hPa. The initial and boundary conditions were obtained from the Model for Ozone And Related Chemical Tracers (Mozart v4.0) (Emmons et al., 2010). Meteorological input data were generated by the Advanced Research Weather Research and Forecasting Model (WRF-ARW, version 3.7) (Skamarock et al., 2008) for the year 2012. The meteorological fields were derived from NCEP FNL (Final) Operational Global Analysis data (NCEP, 2000), with the MODIS land use database (Friedl et al., 2010) and the YSU parametrization (Hong et al., 2006) for the planetary boundary layer.

Six scenarios are simulated in this study: four scenarios represent different reduction technologies (see Table 3); one base case representing business-as-usual; and one scenario without aviation emissions. All scenarios are evaluated for two periods: winter (Jan. 1 - Jan. 15, 2012) and summer (Jul. 8 - Jul. 22, 2012), to explore the seasonal differences in air quality impacts. Both periods were selected according to historical data indicating high levels of ground-level O_3 and $PM_{2.5}$. Please refer to the SI for further detail on the comparison between the simulated episode and the seasonal average ground level SoCAB measured pollutant. The first week of the simulation is discarded to dissipate the effects of the initial conditions. Daily maximum 8 h average O_3 concentrations and 24 h average $PM_{2.5}$ concentrations are calculated and averaged over all simulation days.

2.3.1. Model validation

Model performance is evaluated for both the summer and winter periods using observations from the United States Environmental Protection Agency Air Quality System (AQS) monitoring network. Hourly measurements for O_3 were used to calculate Mean Normalized Gross Bias (MNGB) and Mean Normalized Gross Error (MNGE), and hourly measurements for $PM_{2.5}$ were used to calculate Mean Fractional Bias (MFB) and Mean Fractional Error (MFE). Table 1 shows the statistics for model performance evaluation. Model performance of O_3 satisfied the recommended performance criteria ($|MNGB| \leq 15\%$ and $MNGE \leq 30\%$) proposed by Russell and Dennis (2000), and the statistics of $PM_{2.5}$ also satisfied the model performance criteria proposed by Boylan and Russell (2006) with $MFE \leq 75\%$ and $MFB \leq 60\%$. Additionally, a direct comparison between the simulation results and measurement data is shown on Fig. 2. For ozone, the model correctly

Table 1
Summary of model performance for O_3 and $PM_{2.5}$.

	Summer	Winter
O_3 MNGB	−13%	13%
O_3 MNGE	27%	26%
$PM_{2.5}$ MFB	−16%	−46%
$PM_{2.5}$ MFE	55%	71%

predicted the dural variation for both summer and winter period with small bias (See Fig. 2 (a), (b)). For $PM_{2.5}$, the model also captured the general variation tendency for both period (See Fig. 2 (c), (d)), except an underestimation between Jan.10 and Jan 12.

3. Results and discussion

3.1. Impact on aviation emissions

Emissions from SoCAB airports in 2012 are detailed in Table 2. The column labeled as ‘AEIC estimates’ represents the base case, which depicts a business-as-usual scenario. The AEIC estimates are compared with the ARB's 2012 emission inventory, and their percentage difference is shown in brackets. For a detailed uncertainty discussion, please refer to the SI. Regarding seasonal variability, in the modeled periods of (Jan. 1–15, 2012) and (Jul. 8–22, 2012), the AEIC total summer episode emissions are 15% higher than winter episode emissions.

Emission reductions from SoCAB airports for each scenario are detailed in Table 3. Results are shown as percentage differences from the base case. These emission reductions are calculated according to the methods and data described in section 2.2. Please refer to the SI for the absolute emission values. Although the ALL scenario combines all three strategies, the reduction percentages are lower than the sum of each individual strategy since they reduce emissions through different mechanisms. The TOT scenario is the most effective in reducing hydrocarbon (HC) emissions (13%), as CO and HC are predominantly emitted from low thrust modes used during taxi (Stettler et al., 2011). The GSE scenario significantly reduces the total PM emissions as ground support equipment accounts for 38% of the total organic carbon emitted within SoCAB airports. The GSE scenario achieves an unnoticeable reduction in SO_X emissions due to current regulations mandating the use of ultra-low sulfur diesel. The BIO scenario reduces NO_X by −7%, direct $PM_{2.5}$ emissions by −55%, and SO_x emissions by −68%.

Table 2
SoCAB airport (aircraft and auxiliary power unit) 2012 year emission estimates of AEIC and ARB's 2012 emission inventory (ARB, 2016) for commercial jet aircraft. The percentage difference between the former and the latter is shown in brackets.

Species	Units	AEIC estimates	ARB's 2012 emission inventory
NO_X	kg NO_2	4.23×10^6	4.44×10^6 [-5%]
HC	kg	7.88×10^5	5.46×10^5 [+44%]
SO_X	kg	4.35×10^5	4.45×10^5 [-2%]
$PM_{2.5}$	kg	7.24×10^4	8.03×10^4 [-10%]

Table 3
Percentage change in each pollutant for each scenario versus the base case. Pollutant considered: nitrogen oxides (NOx), hydrocarbons (HC), sulfur oxides (SO_X) and $PM_{2.5}$.

Scenario	Abbreviation	NO_X	HC	SO_X	$PM_{2.5}$
Taxi-Out Time reduction	TOT	−1%	−13%	−5%	−2%
Ground Support Equipment electrification	GSE	−4%	−2%	−0%	−14%
Alternative aviation fuels implementation	BIO	−7%	−1%	−48%	−55%
All previous strategies	ALL	−12%	−17%	−51%	−68%

3.2. Impact on air quality

Ground-level concentrations of O_3 and $PM_{2.5}$ have been computed using CMAQ and they are reported as differences between each scenario and the base case. For base case ground-level concentrations please refer to the SI. Ground-level concentrations of each scenario differ in magnitude but show a similar spatial distribution. Air quality impacts are concentrated in the vicinity of airports, with peak increases for daily maximum 8 h average of O_3 exceeding 2 ppb in summer and peak reductions for 24 h PM2.5 exceeding 1 $\mu g/m^3$ in both seasons. Fig. 3 features a dashed pattern that indicates the non-attainment areas as defined by O_3 8 h average and $PM_{2.5}$ 24 h average NAAQS. For the simulation periods considered in this study, the majority of O_3 increases are localized in areas where the base case concentrations are in attainment. The increases in ozone projected in this study do not cause an exceedance of air quality standards in these areas. Conversely, most of the $PM_{2.5}$ reductions occur in non-attainment areas. These results indicate that the studied environmental mitigation strategies have a positive outcome with respect to regulatory interests, helping to meet $PM_{2.5}$ standards while only raising O_3 concentrations in two small critical areas around the BUR and ONT airports.

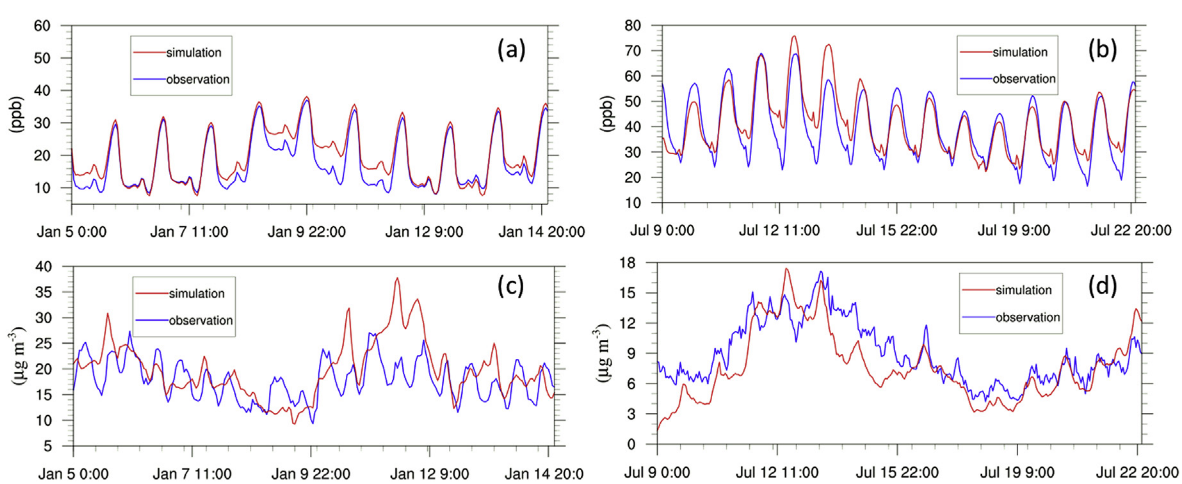

Fig. 2. The time evolution plot between the model (red line) and observation sites (averaged among all sites) for (a) winter ozone, (b) summer ozone, (c) winter $PM_{2.5}$ and (d) summer $PM_{2.5}$. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

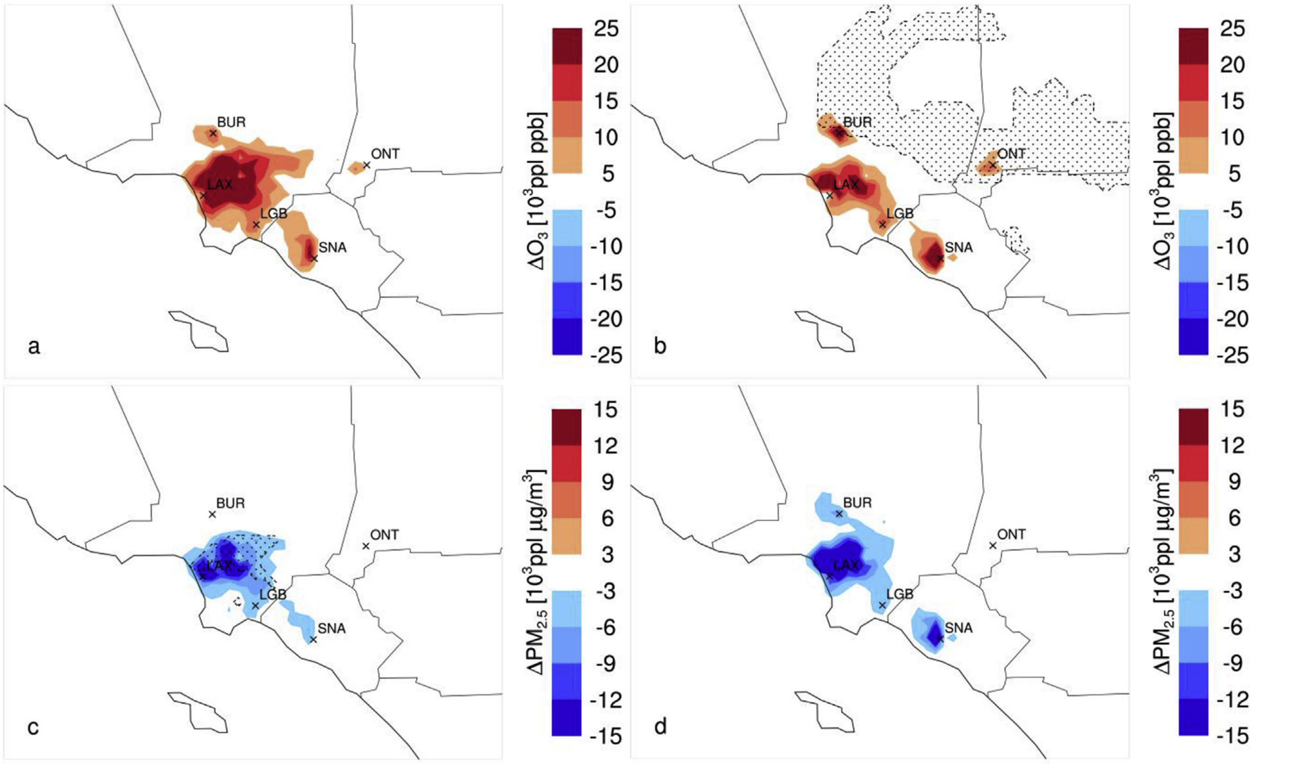

Fig. 3. Population exposure to weekly average changes in maximum daily 8 h average O_3 (top), and 24 h average $PM_{2.5}$ (bottom) during the winter (a, c) and summer (b, d) periods. Differences calculated from ALL scenario minus the base case. The shaded area depicts nonattainment areas for NAAQS (O_3 8 h average > 70 ppb and $PM_{2.5}$ 24 h average > 35 µg/m^3).

Population exposure is a different metric which multiplies inhabitants by pollutant concentration in each grid cell of the domain. Fig. 3 shows the population exposure difference to ground-level O_3 and $PM_{2.5}$ between the ALL scenario and the base case. While pollutant concentration differences are strongly concentrated in the immediate vicinity of airports, Fig. 3 shows that their population exposure attributable impacts affect a larger area. This is due to the location of the strongest emitter airports, upwind of densely populated areas such as Los Angeles.

The total impact of aviation on population exposure is defined as the difference in population weighted average of a pollutant between a given scenario and a scenario with no aviation emissions. Fig. 4 estimates the percentage change in the total aviation attributable impacts on population exposure after applying a reduction strategy. The TOT scenario has a benefit for O_3 and $PM_{2.5}$ in both seasons, due to its greater relative reduction in HC emissions (−13%) than NO_X emissions (−1%). The GSE scenario has worse ozone in summer and winter while only achieving a mean $PM_{2.5}$ reduction of −3%. The implementation of alternative fuels would decrease the total aviation attributable impacts on population $PM_{2.5}$ exposure by −28% in summer and by −19% in winter. It will also raise O_3 attributable impacts by 9% in winter and decrease them by −1% in summer. However, the full implementation of this strategy will come at a social cost. In 2012, the SoCAB aviation relative weight to total emissions was 3%, 9% and 1% for NO_X, SO_X, and $PM_{2.5}$ respectively. Regarding air quality, its relative impact on background concentrations raised O_3 peaks by 3% and decreases $PM_{2.5}$ peaks by 5%. Please refer to the SI for more details. Note that while aviation is not a big pollution source currently, its relative impact will 5-fold by 2050 (Sgouridis et al., 2011), so the total impact of these scenarios will increase accordingly.

The mitigation strategies studied in this paper follow the same trend with respect to population exposure: an increase in O_3 and a decrease in $PM_{2.5}$. To compare these two opposed relative impacts, a cost assessment has been computed with BenMAP-CE (Davidson et al., 2007). This model is used to quantify the premature mortality and morbidity of short-term exposure to ground concentration differences in O_3 and

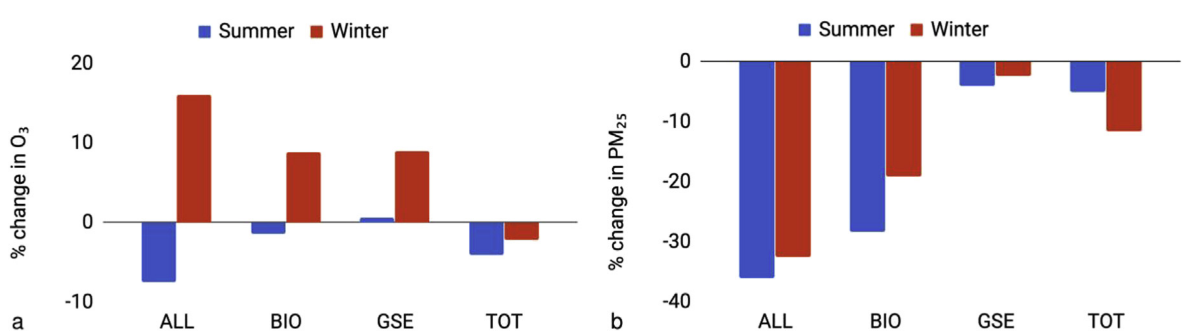

Fig. 4. Percentage change in total aviation attributable population exposure to O_3 (left) and $PM_{2.5}$ (right), computed from the difference in population-weighted average of each case minus no aviation case versus the base case minus no aviation case.

$PM_{2.5}$ in the ALL case minus the base case, with the objective of providing an upper bound. The methods used in the assessment follow the specifications given by the South Coast Air Quality Management District (Shen et al., 2017), with SoCAB specific baseline incidence rates, concentration response functions, and valuation functions. The premature mortality functions for O_3 and $PM_{2.5}$ derived in Bell et al. (2005) and Atkinson et al. (2014) were used respectively. Additional morbidity endpoints were also calculated, please refer to the SI for details. Results show that the reductions in $PM_{2.5}$ costs are 4.7 and 2.9 times the O_3 costs for the summer and winter episodes respectively. Therefore, the air quality impacts will result in a net benefit. For further detail on methods and results please refer to the SI.

All previous strategies combined have the potential to reduce the total aviation attributable impacts on $PM_{2.5}$ population exposure by 36% in summer and 32% in winter. This estimate would partially satisfy US FAA's goal of reducing by 50% the aviation emissions attributable negative health impacts (US FAA, 2012). However, the studied strategies have the potential to increase the contribution of aviation to O_3 by 16% in winter. Due to the VOC-limited nature of urban areas in southern California a slight NO_X emissions reduction increases ground-level O_3. However, future projections indicate a NO_X emissions reduction trend that will result ultimately in a switch to a NO_X-limited regime (Fujita et al., 2013; Zhang et al., 2017). In this event, the projected changes in O_3 would likely be small in magnitude and of variable sign while the $PM_{2.5}$ reductions would persist.

4. Conclusions

This work quantifies the air quality impacts of three environmental mitigation strategies that reduce aviation emissions - taxi-out time reduction, ground support equipment electrification, and alternative aviation fuels implementation - at southern California airports in 2012. Additionally, an aviation emission inventory for the SoCAB has been developed for the year 2012. Ground-level pollutant concentrations changes for each scenario minus the base case are computed with CMAQ, showing a general trend of O_3 increase and $PM_{2.5}$ decrease. Differences in pollutant levels are concentrated around airports in densely populated NAAQS non-compliant areas, where the estimated air quality benefits would help attain such standards. In order to understand the combined effect of an increase in O_3 and a decrease in $PM_{2.5}$ ground level concentrations, their short-term health impacts have been computed using BenMAP-CE. Results show that the benefits of decreasing $PM_{2.5}$ outweigh the costs of increasing O_3 so that the result will be a net benefit. Simultaneous application of all studied mitigation strategies reduces the total aviation attributable impacts on $PM_{2.5}$ population exposure by 36% in summer and 32% in winter. These estimates would partially satisfy US FAA's goal of reducing by 50% the aviation emissions negative health impacts (US FAA, 2012). However, their application can increase the aviation impacts on ground-level O_3 by 16% in winter. This undesired increase in O_3 may diminish if future projections of NO_X emissions reductions eventually switch the chemical regime of the southern California urban areas to NO_X-limited (Fujita et al., 2013; Zhang et al., 2017). In this event, the studied strategies would reduce ground-level concentrations of both $PM_{2.5}$ and O_3.

The taxi-out time reduction strategy is the most efficient at reducing HC emissions (−13%). In VOC-limited urban areas, its application has a positive impact both in O_3 (−3%) and $PM_{2.5}$ (−8%). The ground support equipment electrification strategy slightly reduces NO_X (−4%) and direct $PM_{2.5}$ emissions (−14%). It only reduces ground-level $PM_{2.5}$ by −3%, but it does increase O_3 concentrations by 5%. These two strategies have also the climate co-benefit of reducing fuel burn. Regarding the implementation of alternative aviation fuels scenario, due to the decreased sulfur content in alternative aviation fuels, the emissions of SO_X are reduced by 68% and the direct $PM_{2.5}$ emissions by −55%. However, reducing sulfur emissions has the climate tradeoff of reducing negative radiative forcing (Kapadia et al., 2016). Overall, this strategy alone has the potential to reduce the aviation impacts on ground-level $PM_{2.5}$ by 28% in summer and by 19% in winter. Depending on their origin, alternative fuels are also beneficial for climate by reducing life cycle GHG emissions.

This work has quantified the air quality impacts of implementing multiple environmental mitigation strategies at the airport level. It is important to note that their implementation would likely involve several stakeholders, including airports, airlines, third-party vendors and the FAA, to various extents; as such, further work needs to be conducted to determine feasibility of implementation at specific airports. Further research should also be conducted to assess the air quality implications of other activities necessary for the implementation of these strategies. For instance, production and distribution of alternative aviation fuels to southern California airports may have negative air quality effects that offset its benefits upon end use. This work has quantified the theoretical maximum effect of different concept-proven emissions reduction strategies. Future studies should consider intermediate implementation stages and investigate the resulting impacts on air quality. This study is built upon an emission inventory constructed with a rapid emissions model. The analysis does not consider implementation of these emission reduction strategies in the context of general aviation airports, which Hu et al. (2009) linked with UFP pollution in residential areas. Also, the emissions speciation omits ultrafine particle impacts and the modeling periods are of 2 weeks per season. These issues introduce uncertainty that future works should minimize with more detailed models and longer simulations. Climate co-benefits and tradeoffs were out of scope in this study. Stratton et al. (2011) showed that alternative aviation fuels can have positive or negative impacts on life-cycle GHG emissions depending on their nature and quantification technique, which can outweigh the air quality benefits of proposed strategies.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2018.04.048.

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