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- WRF-STILT model used to determine impacts of wildfire emissions
- Wildfire emissions had episodic impacts in Salt Lake City
- Impacts of wildfires confirmed by observations

Correspondence to:
D. V. Mallia,
Derek.Mallia@utah.edu

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Impacts of upwind wildfire emissions on CO, CO_2, and $PM_{2.5}$ concentrations in Salt Lake City, Utah

D. V. Mallia[1], J. C. Lin[1], S. Urbanski[2], J. Ehleringer[3], and T. Nehrkorn[4]

[1]Department of Atmospheric Sciences, University of Utah, Salt Lake City, Utah, USA, [2]Missoula Fire Sciences Laboratory, Rocky Mountain Research Station, United States Forest Service, Missoula, Montana, USA, [3]Department of Biology, University of Utah, Salt Lake City, Utah, USA, [4]Atmospheric and Environmental Research Inc., Lexington, Massachusetts, USA

Abstract Biomass burning is known to contribute large quantities of CO_2, CO, and $PM_{2.5}$ to the atmosphere. Biomass burning not only affects the area in the vicinity of fire but may also impact the air quality far downwind from the fire. The 2007 and 2012 western U.S. wildfire seasons were characterized by significant wildfire activity across much of the Intermountain West and California. In this study, we determined the locations of wildfire-derived emissions and their aggregate impacts on Salt Lake City, a major urban center downwind of the fires. To determine the influences of biomass burning emissions, we initiated an ensemble of stochastic back trajectories at the Salt Lake City receptor within the Stochastic Time-Inverted Lagrangian Transport (STILT) model, driven by wind fields from the Weather Research and Forecasting (WRF) model. The trajectories were combined with a new, high-resolution biomass burning emissions inventory—the Wildfire Emissions Inventory. Initial results showed that the WRF-STILT model was able to replicate many periods of enhanced wildfire activity observed in the measurements. Most of the contributions for the 2007 and 2012 wildfire seasons originated from fires located in Utah and central Idaho. The model results suggested that during intense episodes of upwind wildfires in 2007 and 2012, fires contributed as much as 250 ppb of CO during a 3 h period and 15 $\mu g/m^3$ of $PM_{2.5}$ averaged over 24 h at Salt Lake City. Wildfires had a much smaller impact on CO_2 concentrations in Salt Lake City, with contributions rarely exceeding 2 ppm enhancements.

1. Introduction

Fires from biomass burning are responsible for emitting large quantities of CO_2, CO, and $PM_{2.5}$ into Earth's atmosphere. Biomass burning has been suggested to account for as much as 15–30% of global CO emissions [*Galanter et al.*, 2000; *Intergovernmental Panel on Climate Change* (*IPCC*), 2013]. In the western U.S. during active years, wildfire emissions of CO and $PM_{2.5}$ can account for up to 20% and 40% of total annual emissions, respectively [*Urbanski et al.*, 2011]. On average, CO_2 emission from wildfires in the United States comprises 4–6% of anthropogenic emissions [*Wiedinmyer and Neff*, 2007].

In addition to gaseous species such as CO_2 and CO, fires can also release large quantities of particulate matter [*Davies and Unam*, 1999; *Sapkota et al.*, 2005; *Park et al.*, 2007]. Particulate matter with an aerodynamic dynamic diameter < 2.5 μm ($PM_{2.5}$) is a criteria pollutant that is regulated by the U.S. Environmental Protection Agency (EPA) [*U.S. Environmental Protection Agency* (*EPA*), 2011]. EPA has established national ambient air quality standards (NAAQS) for both short-term and long-term exposure to $PM_{2.5}$. Compliance with the short-term standard of 35 $\mu g/m^3$ is evaluated as the 3 year average of the 98th percentile of the daily maximum 24 h average concentration, and compliance with the long-term standard of 12 $\mu g/m^3$ is evaluated as the 3 year average of the annual mean $PM_{2.5}$ concentration [*EPA*, 2011]. High concentrations of $PM_{2.5}$ can have adverse effects on human health, as these particulates can be easily inhaled enabling them to penetrate deep into the lungs [*EPA*, 2011]. The elderly, young children, and people with lung and heart diseases are the most susceptible to increased concentrations of $PM_{2.5}$ [*EPA*, 2011; *Beard et al.*, 2012]. In urban areas of the Intermountain West, NAAQS for $PM_{2.5}$ and ozone continue to be violated [*EPA*, 2011; *Chen et al.*, 2012; *Lareau et al.*, 2013; *Silcox et al.*, 2012].

The western U.S. is the primary source of wildfire emissions in the U.S., due to arid conditions, the abundance of needleleaf forests, and a dry season [*Westerling et al.*, 2006; *Wiedinmyer and Neff*, 2007]. The greatest

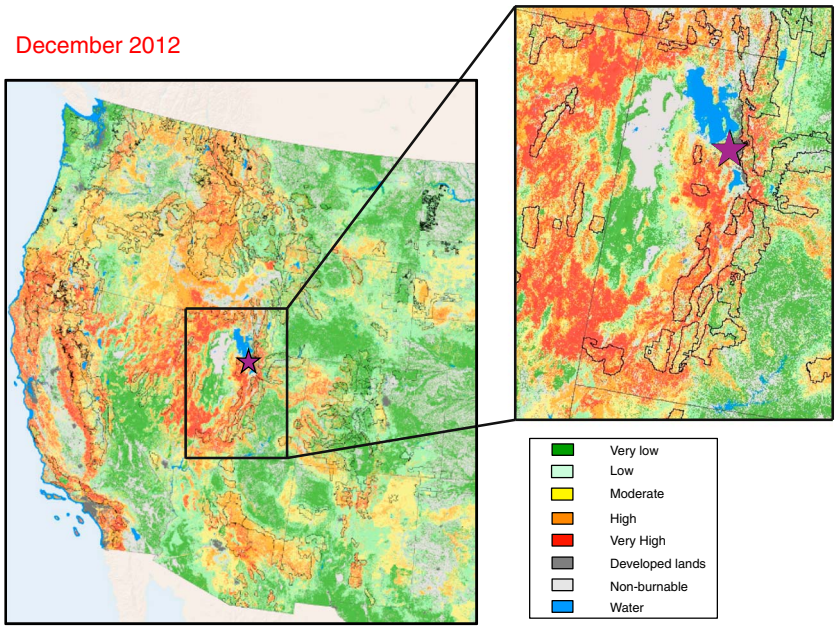

Figure 1. The Wildland Fire Potential product for the western U.S [*Missoula Fire Laboratory*, 2013]. The shaded values represent the wildfire potential risk beyond 2012 while the purple star represents the location of downtown SLC.

wildfire emissions occur between the months of June and October, with maximum emissions occurring in August [*Wiedinmyer and Neff*, 2007; *Urbanski et al*., 2011]. *Dennison et al*. [2014] noted a general increase in large wildfires (>405 ha) across the western U.S. from 1984 through 2011. Annual western U.S. burned areas have also been on the increase since the 1970s according to observed and reconstructed databases that span from 1916 to 2004 [*Littell et al*., 2009]. These changes have been attributed to higher annual mean temperatures that result in earlier snowmelt and land use changes that prolong the wildfire season [*Westerling et al*., 2006; *Dennison et al*., 2014; *Riley et al*., 2013]. This trend is likely to continue with the average maximum air temperature and drought severity increasing for these regions under the Intergovernmental Panel on Climate Change's moderate emission scenario A1B [*IPCC*, 2013].

This study focuses on wildfires in the western United States and their impacts on CO, CO_2, and $PM_{2.5}$ concentrations in Salt Lake City (SLC), in the state of Utah. SLC is one of the major urban centers located in the Intermountain West with a population that is projected to double in size by the year 2050 [*Utah Foundation*, 2014]. The area surrounding SLC is also prone to wildfire activity, as indicated by the Wildland Fire Potential product, from the Fire Program Analysis system (Figure 1) [*Missoula Fire Laboratory*, 2013; *Finney et al*., 2011]. Concentrations of CO, CO_2, and $PM_{2.5}$ can become further amplified in regions like the SLC valley due to strong surface inversions that are influenced by the surrounding topography. While CO_2 does not have any direct impacts on air quality, it is an inert gas that is a suitable tracer for atmospheric transport, thereby allowing us to evaluate the validity of simulated transport [*Pataki et al*., 2006].

Wildfires have the potential to enhance concentrations of pollutants regulated by the EPA in downwind regions, e.g., CO, $PM_{2.5}$, and O_3 [*Clinton et al*., 2006; *Bravo et al*., 2002; *Davies and Unam*, 1999; *Debell et al*., 2004; *Sapkota et al*., 2005; *Dempsey*, 2013]. For example, wildfires in Quebec during the summer of 2002 injected large quantities of CO and $PM_{2.5}$ into the mixed layer of the atmosphere that were later transported by midlevel winds to the northeastern U.S [*Debell et al*., 2004; *Sapkota et al*., 2005]. During this period, CO and $PM_{2.5}$ monitoring stations across the Northeast noted elevated concentrations, which occurred during the passage of the smoke plumes originating from the Quebec wildfires [*Debell et al*., 2004; *Sapkota et al*., 2005]. A similar situation was observed when smoke from wildfires in northern Saskatchewan was transported over Toronto, resulting in elevated levels of $PM_{2.5}$ and O_3 [*Dempsey*, 2013]. If the passage of a smoke plume occurs in an urban area during the morning or afternoon rush hours, when traffic emissions are maximized, very high CO concentrations can be observed [*Debell et al*., 2004; *Sapkota et al*., 2005; *Dempsey*, 2013].

Previous studies have determined the influences of wildfire emissions on downwind locations using qualitative methodologies [*Debell et al*., 2004; *Sapkota et al*., 2005; *Dempsey*, 2013]. However, these studies have been unable to quantify the direct influences from these fires. Cities across the western U.S. have often exceeded the NAAQS for $PM_{2.5}$ and O_3 during the summer months due to increased wildfire activity [*EPA*, 2010; *Utah's Division of Air Quality* (*UDAQ*), 2013, 2012b; *Jaffe et al*., 2013; *Jaffe and Wigder*, 2012]. However, as of 2007, the EPA has adopted a new regulation, the Treatment of Data Influenced by Exceptional Events (EER), which allows every state to flag data in EPA's Air Quality System database for events that are not reasonably controllable or preventable and are natural. For an event to be considered "exceptional" by the definitions set forth by EPA [*EPA*, 2013], it has to be demonstrated that the event meets the following criteria: (1) associated with measured concentrations in excess of historical fluctuations, (2) a clear relationship between the flagged measurements and the event, and (3) no exceedance would have taken place had the exceptional even not occurred. Here we will use a source apportionment modeling method that will attempt to separate the impacts of nonwildfire emissions from wildfire-emitted CO_2, CO, and $PM_{2,5}$. This modeling framework will make use of state-of-the-art Lagrangian and Eulerian atmospheric models along with the latest wildfire emission inventories in order to determine the influences of upwind wildfire emissions on SLC. Going forward, this modeling framework has the potential to allow air quality managers to quantify the impact of wildfire events on air quality.

2. Methodology

The Weather Research and Forecasting (WRF) model was coupled with the Stochastic Time-Inverted Lagrangian Transport (STILT) particle dispersion model to determine the impacts of upwind wildfire emissions on CO, CO_2, and $PM_{2.5}$ concentrations in SLC [*Skamarock et al*., 2008; *Lin et al*., 2003]. WRF is a Eulerian nonhydrostatic atmospheric model equipped with a large suite of physical parameterizations. Backward trajectory ensembles arriving at SLC used to model CO, CO_2, and $PM_{2.5}$ were generated using the STILT model driven by the WRF wind fields. A Lagrangian framework like STILT offers several benefits over Eulerian tracer models in the Lagrangian formulation's physical realism, numerical stability, lack of numerical diffusion, adherence to mass conservation, and computational efficiency [*Lin et al*., 2013; *Wohltmann and Rex*, 2009; *Shin and Reich*, 2009; *Smolarkiewicz and Pudykiewicz*, 1992; *McKenna et al*., 2002].

Surface flux footprints $f(x_r, t_r|x_i, y_j, t_m)$ for a receptor at location x_r and time t_r to an upwind source at (x_i, y_j) and prior time t_m can be estimated from the WRF-STILT backward trajectories [*Lin et al*., 2003; *Nehrkorn et al*., 2010; *Skamarock et al*., 2008]. The footprint is simply the measure of the upwind surface influences for a receptor as determined by the STILT backward trajectories. The footprint is a function of the number of Lagrangian particles within the planetary boundary layer (PBL) for some upwind location and has units of mixing ratio per unit surface flux as seen in the equation below:

$$f\left(x_r, t_r \middle| x_i, y_j, t_m\right) = \frac{m_{\text{air}}}{h\overline{\rho}\left(x_i, y_j, t_m\right)} \frac{1}{N_{\text{tot}}} \sum_{p=1}^{N\text{tot}} \Delta t_{p,i,j,k} \tag{1}$$

where m_{air} is the molecular weight of air, h is the height of the volume in which the surface fluxes are diluted over (surface influence volume), ρ is the average density for all particles, N_{tot} is the total number of particles, and $\Delta t_{p,i,j,k}$ is the amount of time a particle p spends within the surface influence volume at location (x_i, y_j) and time t_m [*Lin et al*., 2003; *Wen et al*., 2012; *Kim et al*., 2013; *Lin et al*., 2013]. Any surface fluxes that occur within the PBL are assumed to be rapidly mixed within the surface influence volume, which is taken to extend from the surface to a height of 0.5 z_i (one half of the PBL height). Previous studies have indicated that simulated STILT footprints were insensitive to the exact value of the column height "h" as long as h was between 10 and 100% of the PBL height [*Lin et al*., 2003; *Gerbig et al*., 2003].

Multiplying the footprint field with fluxes of CO, CO_2, and $PM_{2.5}$ allows us to determine the direct contribution of upwind source regions on the total concentration of CO, CO_2, and $PM_{2.5}$ arriving at the receptor. Simulations were carried out for the 2007 and 2012 wildfire seasons, which were characterized by significant emissions in the western U.S. (see section 3) The wildfire season is defined as the months of June through October [*Westerling et al*., 2006].

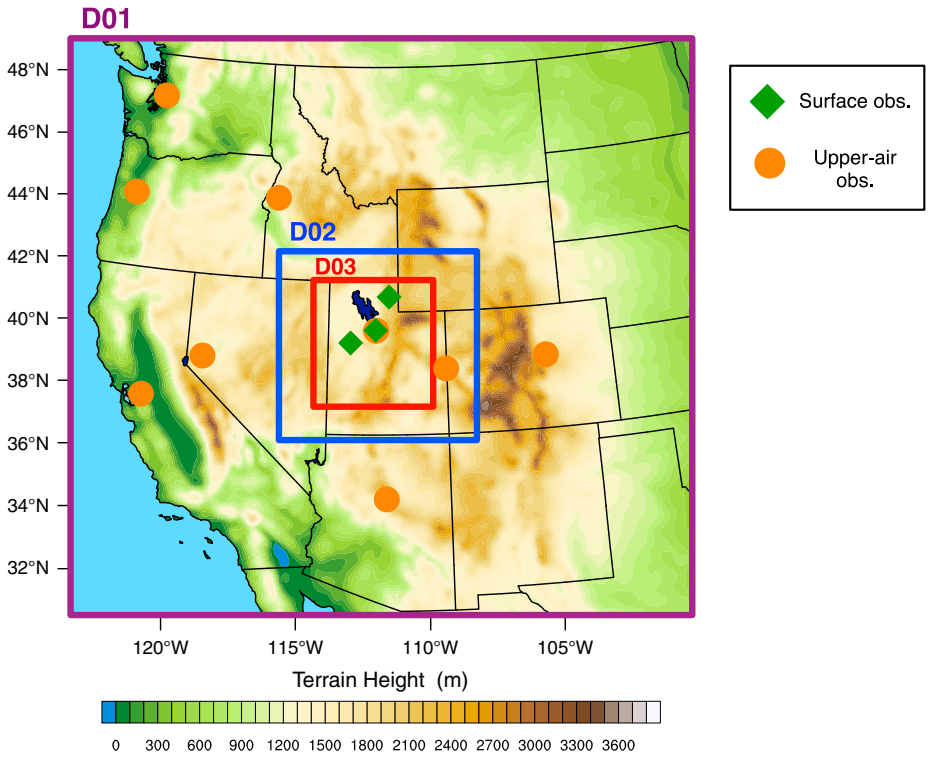

Figure 2. The WRF domain used for this study with surface and upper air observations used for our WRF run comparisons. The horizontal grid spacing is 12 km for D01, 4 km for D02, and 1.333 km for D03.

2.1. WRF-STILT Model Configuration

The Advanced Research version of the WRF model (ARW, version 3.4.1) [*Skamarock et al.*, 2008] was used to drive the backward trajectories created by the STILT model. Boundary conditions were provided by the North American Regional Reanalysis (NARR) which is available at a horizontal grid spacing of 32 km with 30 vertical levels every 3 h [*Mesinger et al.*, 2006]. Our WRF simulations consisted of three domains at 12, 4, and 1.33 km resolution with two-way nesting (Figure 2). Outside of the WRF domain (Figure 2), the Global Data Assimilation System final analysis (FNL) (1° resolution every 6 h) was used to drive STILT.

Time-averaged, mass coupled winds from the WRF model were used to improve mass conservation and the temporal representation of wind variation [*Nehrkorn et al.*, 2010; *Hegarty et al.*, 2013]. The native vertical levels within STILT were selected to closely match the WRF vertical levels to further improve mass continuity. WRF simulations were carried out from the beginning of June to the end of October with hourly output for 2007 and 2012. Previous research has indicated that output frequencies higher than 3 h for high-resolution meteorology fields are needed to further reduce interpolation errors within Lagrangian particle dispersion models like STILT [*Bowman et al.*, 2013]. WRF simulations were reinitialized every 7 days and were allowed to have a spin-up time of 12 h. The first 12 h of each run were then replaced with the last 12 overlap hours from the previous WRF simulation.

WRF simulations using a variety of physical parameterizations and nudging techniques were compared against National Weather Service regional and local upper air and surface observation sites in order to determine the optimal settings (Figure 2). Ten different WRF simulations centered over SLC were carried out for the month of July 2007 using a variety of configurations involving different parameterizations and grid nudging setups (Table 1). All model runs had 41 vertical levels with 10 of these levels within 1 km of the surface in order to better resolve circulations within the PBL. The model top was located at the 50 hPa pressure level. It should be noted that certain runs used the 2006 National Land Cover Database, which is denoted as "yes" under the land use column in Table 1. Runs denoted with a "no" under the land use column in Table 1 simply used the default WRF land use database. These model runs also adopted a two-way nested

Table 1. Overview of the WRF Configurations Tested for the WRF Simulations Centered Over Salt Lake City for July 2007[a]

Run #	Nudging	Microphysical	Cumulus	PBL	Urban?	Land Use?	RMSE *u* Wind (m/s)	RMSE *v* Wind (m/s)	RMSE Temperature (°C)	BIAS *u* Wind (m/s)	BIAS *v* Wind (m/s)	BIAS Temperature (°C)
#1	Spectral nudging above PBL	New Thompson	Kain-Fritsch	YSU	No	No	3.45	3.30	1.96	0.71	−0.48	−0.13
#2	Spectral nudging at all levels	New Thompson	Kain-Fritsch	YSU	No	No	3.05	3.04	1.93	−0.06	−0.18	−0.18
#3	No nudging	New Thompson	Kain-Fritsch	YSU	No	No	3.42	4.00	2.39	1.06	−1.11	−0.48
#4	No nudging	WSM 3-class	Kain-Fritsch	MYJ	Yes	No	3.89	3.77	2.11	−0.05	−0.81	−0.81
#5	No nudging	New Thompson	Betts-Miller-Janjić	MYJ	Yes	No	3.86	3.74	2.07	0.97	−0.99	−0.49
#6	Grid nudging above PBL	Purdue Lin	Grell-Devenyi Ens.	YSU	Yes	No	2.72	2.66	1.69	0.81	−0.54	−0.27
#7	Grid nudging above PBL	Purdue Lin	Grell-Devenyi Ens.	MYJ	Yes	No	2.76	2.67	1.63	0.81	−0.50	−0.36
#8	Grid nudging above PBL	Purdue Lin	Grell-Devenyi Ens.	MYJ	Yes	Yes	2.80	2.71	2.01	0.80	−0.52	0.31
#9	Spectral nudging above PBL	Purdue Lin	Grell-Devenyi Ens.	MYJ	Yes	Yes	4.00	3.80	2.24	1.06	−1.11	−0.46
#10	No nudging	Purdue Lin	Grell-Devenyi Ens.	MYJ	Yes	Yes	3.16	3.00	1.81	0.62	−0.45	−0.20

[a]All of these simulations used the RRTMG longwave and shortwave radiation schemes, NOAH land surface model, and had a similar domain with 41 vertical levels. Also included is the averaged RMSE and model BIAS (model-observation) for all upper air and surface observations for the *u* and *v* wind components and temperature.

grid with boundary conditions obtained from the NARR [*Mesinger et al*., 2006]. All simulations used the Rapid Radiative Transfer Model for GCMs (RRTMG) longwave and shortwave radiation schemes [*Iacono et al*., 2008] and the NOAH land surface model [*Chen and Dudhia*, 2001].

The root-mean-square error (RMSE) and model biases (model-observation) were calculated using surface and upper air observations across the western U.S. in order to determine the errors associated with each model run (Table 1). These statistics were calculated for horizontal wind components (*u*, *v*) as well as temperature, since these variables are key determinants, respectively, of air parcel trajectories and stability within the STILT simulations. The RMSE and model bias at all observation stations were then averaged over July 2007 to arrive at an average error statistic for each WRF run as seen in Table 1.

The WRF simulations that utilized settings discussed in *Nehrkorn et al*. [2013] (WRF runs #6 and 7) exhibited the best performance when compared against surface and upper air observations. These simulations used the Purdue Lin scheme for microphysics and the Grell-Devenyi ensemble scheme for the cumulus parameterization in domain 1 only, with the urban canopy model switched on [*Grell and Devenyi*, 2002; *Lin et al*., 1983]. Grid nudging was also switched on for the horizontal wind components and temperature for all WRF vertical levels above the PBL for domain 1 only with a nudging coefficient of $3 \times 10^{-4}\,s^{-1}$. WRF#6 had the lowest average RMSE for the *u* and *v* wind components (2.72 and 2.66 m/s) while WRF#7 had the lowest RMSE for temperature (1.63°C). Both of these runs also exhibited small biases for wind vectors and temperature (Table 1).

In addition to these error statistics, the vertical profiles of potential temperature (θ) from each of these runs were compared to the Salt Lake City Airport (KSLC) upper air observation site at the SLC airport (40.79°N, −111.98) at 0000 and 1200 UTC (Figure 3).

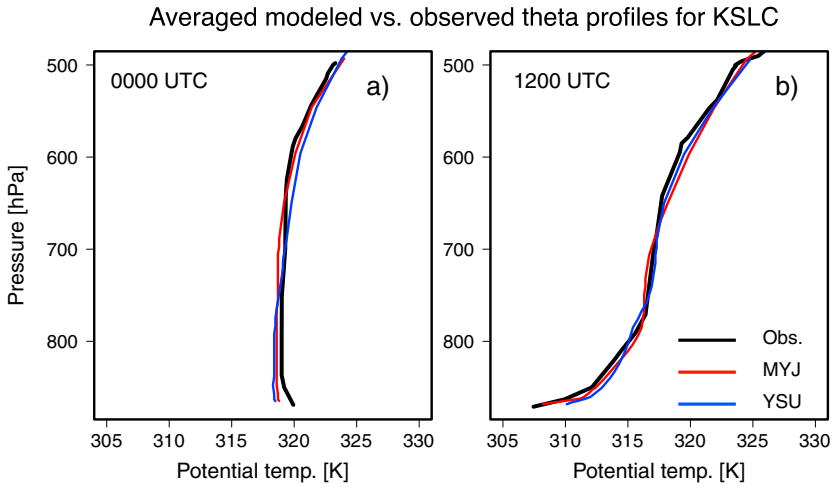

Figure 3. (a) Comparisons between the averaged 0000 UTC upper air observations and modeled potential temperature profiles for KSLC during the month of July 2007. (b) The average for the 1200 UTC potential temperature profiles. The black lines are the observed values, the red lines are the modeled values using the MYJ scheme, and the blue lines are modeled values using the YSU scheme.

STILT-simulated footprint strengths are dependent on whether the meteorological model driving STILT accurately resolves the PBL height. Resolving inversion events in mountain valleys like the SLC valley can be especially difficult for numerical weather models [*Chen et al*., 2012; *Lareau et al*., 2013; *Silcox et al*., 2012; *Reeves et al*., 2011]. Furthermore, CO_2 and CO concentrations within SLC exhibit a strong diurnal signal that is dependent on the growth/decay of the PBL, further necessitating accurate simulations of the PBL [*Strong et al*., 2011; *Nehrkorn et al*., 2013; *McKain et al*., 2012].

The θ profiles for WRF#6 and #7 were averaged for the month of July 2007 and were plotted against the KSLC upper air observation site (Figure 3). Both WRF simulations over KSLC for 0000 UTC showed a slight cool bias below the 750 hPa pressure level, with minimal differences separating the two runs (Figure 3a). However, the WRF simulation that adopted the 1.5-order-closure Mellor-Yamada-Janjić PBL scheme (MYJ; WRF#7) did a better job resolving nocturnal inversions when compared to WRF#6 which used the first-order-closure, eddy-diffusivity turbulence Yonsei-University PBL scheme (YSU) (Figure 3b) [*Mellor and Yamada*, 1982; *Hong et al*., 2006]. This is in accordance with the results found in *Nehrkorn et al*. [2013] who also concluded that WRF simulations using the MYJ PBL scheme performed the best in resolving the near-surface θ profile at SLC. Henceforth, WRF#7 was chosen as the optimal WRF configuration for all subsequent simulations.

The STILT model was run with multiple particles that traveled 72 h backward in time, with a time step of 2 min for the mean-wind component (and turbulence time steps on the order of seconds). Unlike single-trajectory models, STILT simulates backward trajectories as an ensemble to account for the random turbulence air parcels experience, particularly while traveling within the PBL [*Lin et al*., 2013]. A particle ensemble size of 2000 was chosen, following the sensitivity analysis described below. Theoretically, an extremely large number of particles are needed to represent the ensemble properties of atmospheric transport. Due to finite computational resources and lack of meteorological input that can comprehensively parameterize eddy motions, only an ensemble of limited size can be simulated. A limited number of particles can lead to incomplete sampling of particle trajectories and emissions, which can cause modeled concentrations to fluctuate depending on the size of the particle ensemble, with the fluctuation decreasing as the particle number increases [*Gerbig et al*., 2003]. To assess the magnitude of these fluctuations as a function of ensemble size, 50 STILT simulations for CO were run for each ensemble size on 15 August 2012 at 0000 UTC (Figure 4). This particular day was chosen as there were significant wildfire contributions toward SLC's CO concentrations at this time. The standard deviation of these simulations was calculated for each ensemble size in order to quantify the sensitivity of the STILT model (Figure 4). As expected, the model shows the most sensitivity to ensemble size when simulating the contributions from distant point sources, which was the case for the wildfire contributions seen in Figure 4. On the other hand, limited sensitivity to ensemble size was observed in the simulated background concentrations, likely due to its smaller spatial

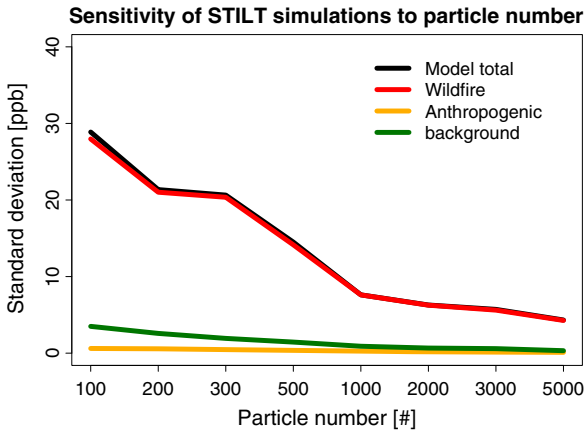

Figure 4. Fluctuations in STILT-simulated CO as a function of the particle ensemble size, i.e., number of particles. The standard deviation of 50 different STILT runs to simulate CO from different components (total, wildfire, anthropogenic, and background) arriving at SLC for 15 August 2012 is calculated for each particle ensemble size.

variability and the fact that the STILT particles are already highly dispersed at the end of the 72 h simulation. The anthropogenic contributions also exhibited a limited amount of sensitivity to the ensemble size as most of these contributions originated locally from sources within the SLC valley. An ensemble size of 2000 was chosen since model fluctuations appeared to be highly damped.

2.2. Wildfire Emissions

Wildfire CO, CO_2, and $PM_{2.5}$ emissions for the western U.S. were obtained from an updated version of the Wildland Fire Emissions Inventory (WFEI) [*Urbanski et al.*, 2011]. The updated WFEI includes new CO and $PM_{2.5}$ emission factors for forest fires [*Urbanski*, 2013]. For 2012, the Moderate Resolution Imaging Spectroradiometer (MODIS Direct Broadcast)-based burned area used in WFEI was unavailable and alternate sources of burned area maps were employed. Daily burned area was based on a combination of fire perimeter polygons collected by the U.S. Geological Survey GeoMAC (http://wildfire.usgs.gov/geomac/index.shtml) and a daily MODIS burn scar product produced by the U.S. Forest Service Remote Sensing Applications Center (http://activefiremaps.fs.fed.us/burnscar.php) using the algorithm of *Giglio et al.* [2009]. Fire perimeter area not mapped by the daily MODIS burn scar product was assigned an estimated burn date using active fire detections from the MODIS MXD14 product [*Giglio et al.*, 2003] and NOAA's Hazard Mapping System (http://www.ssd.noaa.gov/PS/FIRE/hms.html). The 2012 emission product also integrated significant updates for vegetation maps and fuel loading. Forest vegetation type and fuel loading were assigned based on a Forest Type Group map [*Ruefenacht et al.*, 2008] and the forest surface fuel classification of *Keane et al.* [2013]. The surface fuel loading was augmented with fuel loading estimates of understory fuels [*Wilson et al.*, 2013] and canopy fuels, the latter of which was estimated from canopy spatial data layers from the LANDFIRE project [*LANDFIRE*, 2014]. Area mapped as nonforest in the Forest Type Group map was assigned fuel loading from a MODIS normalized difference vegetation index-based rangeland biomass product (M. Reeves, manuscript in preparation, 2014). Forest canopy fuel consumption was taken as 50% while consumption of other fuel components was estimated using the First-Order Fire Effects Model assuming "dry" conditions (see *Urbanski et al.* [2011] for details). As in the 2007 emission data set, CO and $PM_{2.5}$ emission factors for forest fires were taken from *Urbanski* [2013]. For both 2007 and 2012 the heat flux was estimated using a heat of combustion of 18.6 MJ kg^{-1} biomass [*Susott et al.*, 1975; *Klass*, 1998]. The WFEI is available daily at 500 m grid spacing for years between 2003 and 2008, as well as 2012. Annual, domain-wide uncertainties within the WFEI range from 28 to 51% for CO emissions and 40–65% for $PM_{2.5}$ emissions [*Urbanski et al.*, 2011]. Emissions from the WFEI were regridded to latitude/longitude grids with a spatial resolution of 0.1° × 0.1° to match the WRF-STILT footprint grid. Finally, the WFEI daily emissions were scaled by time of day using daily factors obtained from the Global Fire Emissions Database v3.1 [*Mu et al.*, 2010; *van Der Werf et al.*, 2010].

2.3. Anthropogenic Emissions

Global anthropogenic CO_2 and CO emissions were obtained from the Emission Database for Global Atmospheric Research (EDGAR), which has a spatial resolution of 0.1° × 0.1° and is available from 1970 through 2010 [*European Commission*, 2009]. Previous CO_2 modeling studies for the SLC area used the VULCAN database [*Gurney et al.*, 2009] for an anthropogenic CO_2 emissions field [*Strong et al.*, 2011; *Nehrkorn et al.*, 2013; *McKain et al.*, 2012]. However, these researchers found VULCAN-derived simulations to consistently underestimate CO_2 concentrations across the SLC valley [*Nehrkorn et al.*, 2013; *McKain et al.*, 2012]. *Nehrkorn et al.* [2013] hypothesized that the systematic underprediction of CO_2 was caused by an overestimation of mixing by the WRF model and/or an underestimation in anthropogenic emissions predicted by VULCAN.

Initial findings in this study found that the systematic underestimation of CO_2 was removed when using the EDGAR data set scaled by hour of day for anthropogenic emissions (not shown). Scaling factors were needed for time of day for CO and CO_2 due to the fact that EDGAR only reports annual emissions. Hourly scaling factors for CO emissions in northern Utah were computed by dividing the Utah's Division of Air Quality (UDAQ) SMOKE emissions (hourly temporal resolution for the summer of 2007) by the annual EDGAR emissions. UDAQ SMOKE emissions were not available outside of July 2007 and were limited to northern Utah, so these emissions could not be used directly within WRF-STILT. The hourly scaling factors for CO were then applied back to the EDGAR emissions based on the time of day. This methodology was only applied to emissions for northern Utah due to domain constraints in UDAQ SMOKE inventory. This is a reasonable approximation, since we found that anthropogenic emissions beyond northern Utah only account for ~3–5% of the anthropogenic CO arriving at SLC, on average. A similar methodology was applied to the EDGAR CO_2 emissions using time-of-day scaling factors obtained from VULCAN. A simple linear trend was then calculated for EDGAR CO emissions from 2000 to 2008, in order to extrapolate CO emissions to 2012.

2.4. Biospheric Fluxes

The biospheric flux fields within CarbonTracker-2013, which utilized the Carnegie-Ames-Stanford Approach model [*Potter et al*., 1996, 1999; *Potter and Klooster*, 1997], were used to obtain biospheric CO_2 fluxes. CarbonTracker is a CO_2 assimilation system developed by NOAA in order to quantify the sources and sinks of CO_2 over the globe [*Peters et al*., 2007]. The CarbonTracker biospheric flux field is available every 3 h from 2010 through 2012 with a horizontal grid resolution of 1 × 1° for North America.

2.5. Background CO and CO_2 Concentrations

CarbonTracker-2013's 3-D fields of CO_2 were applied as background concentrations by taking the endpoints of the 2000 particle ensemble members and interpolating them to the corresponding grid cell 72 h backward in time. The background concentrations at the trajectory endpoints are then simply advected to the receptor location. The global CarbonTracker-2013 data set has a gridded resolution of 3 × 2° at the global scale and 1 × 1° for North America with a temporal resolution of 3 h. For CO, the Model for Ozone and Related Chemical Tracers (MOZART-4) database [*Emmons et al*., 2010] was used to obtain background concentrations using the same methodology described for CO_2 with the exception that oxidation with OH is applied throughout the STILT trajectory pathways (discussed in the next section). The MOZART-4 model has a global domain with a gridded resolution of 2.8 × 2.8° with a temporal resolution of 6 h. Uncertainties in background CO concentrations as simulated by MOZART are approximately 15 ppb [*Emmons et al*., 2010].

2.6. Chemical and Depositional Losses

Chemically reactive species such as CO and $PM_{2.5}$ undergo transformations as they are transported through the atmosphere. Using the methodology described in *Miller et al*. [2008], we applied a first-order chemical loss due to reactions with OH to the CO simulations. Six-hourly OH concentrations were obtained from MOZART-4. The loss of CO due to the presence of OH in the atmosphere can be described by the following equation:

$$\frac{\partial[\mathrm{CO}]}{\partial t} = -k[\mathrm{OH}][\mathrm{CO}] \tag{2}$$

where k is the oxidation rate constant obtained from the *NASA's Jet Propulsion Laboratory*'s [2011] chemical kinetics publication. This reaction was applied to each STILT particle at 2 min time steps.

$PM_{2.5}$ is influenced by dry/wet deposition (sink) and secondary formation from chemical reactions with other species (source). Dry deposition survival rates were obtained by applying a size-segregated particle dry deposition scheme developed by *Zhang et al*. [2010] to the STILT trajectories. Dry deposition was only applied to particles that dipped below the STILT model PBL height. The diameter and particle density of wildfire-emitted $PM_{2.5}$ used in this scheme were assumed to be 0.25 μm and 1.3 g/cm^3, respectively [*Reid et al*., 2005]. The wet deposition rates for $PM_{2.5}$ along each trajectory path were calculated using an adaption of the GEOS-Chem wet deposition scheme, which assumes that aerosols are hydrophilic [*Liu et al*., 2001]. Both dry and wet deposition were calculated every 2 min along each trajectory. The secondary

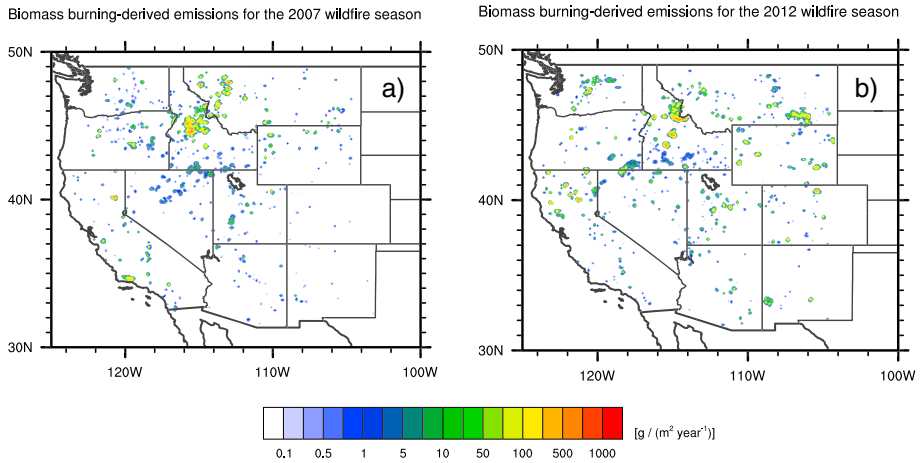

Figure 5. Total wildfire emissions for the (a) 2007 and (b) 2012 western U.S. wildfire season as derived from the updated WFEI.

formation of $PM_{2.5}$ was excluded from the WRF-STILT model framework due to the complexity of $PM_{2.5}$ reactions with other chemical species. Incorporating the secondary formation of $PM_{2.5}$ will be part of a future study.

2.7. Observation Networks

Near-surface CO_2 concentrations have been measured continuously since 2001 across much of Salt Lake valley using a network of infrared gas analyzers [*Pataki et al.*, 2003, 2006; *Ehleringer et al.*, 2008, 2009]. This particular study focused on the Sugarhouse site, which is approximately 3 miles equals 5 km (approximation) to the southeast of downtown SLC (40.73°N, −111.86°W).

CO and $PM_{2.5}$ measurements were obtained from the UDAQ's Hawthorne site (40.73°N, −111.87°W) in SLC, which is maintained by UDAQ and is approximately 1 km to the west of the Sugarhouse CO_2 monitoring site. The Tapered Element Oscillating Microbalance Filter Dynamic Measuring System was used to obtain hourly $PM_{2.5}$ concentration while CO measurements were obtained using the Instrumental Gas Phase Correlation [*UDAQ*, 2012a]. Measurements of potassium ion and organic carbon concentrations were

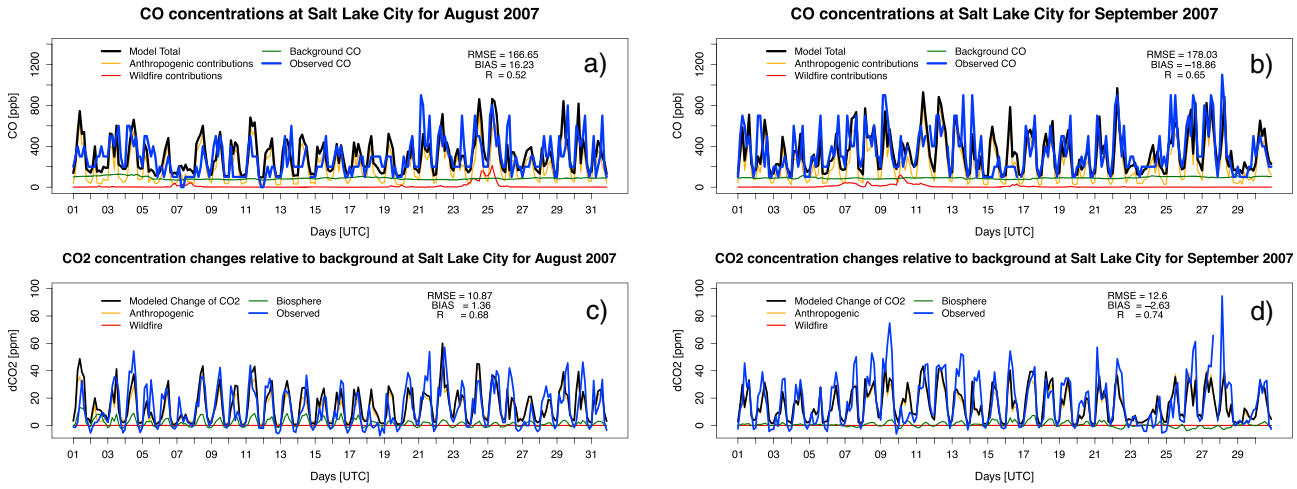

Figure 6. (a and b) STILT-simulated and observed CO concentrations at SLC during August and September 2007. The black line is modeled total CO, while the orange, red, and green lines are contributions from anthropogenic and fire emissions and the background CO. The blue line is the observed CO concentrations at SLC. (c and d) STILT-simulated and observed CO_2 concentrations at SLC during August and September 2007. The black line is the modeled total CO_2 while the orange, red, and green lines represent the source contributions.

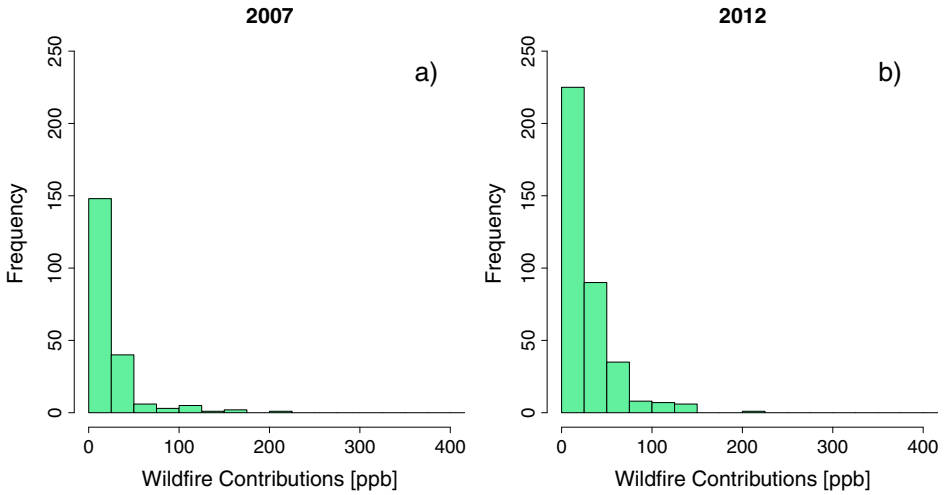

Figure 7. Frequency of 3-hourly wildfire contributions to SLC CO concentrations for the (a) 2007 and (b) 2012 western U.S. wildfire seasons. Wildfire contributions ≥5 ppb are included in the lowest bin.

obtained from UDAQ. The Hawthorne observation site is one of three urban $PM_{2.5}$ chemical speciation monitors that are part of EPA's Speciation Trends Network [*UDAQ*, 2012a]. Potassium ion and organic carbon are considered good biomarkers for wood smoke and were later used to verify periods of increased wildfire activity simulated by the STILT model [*Pachon et al.*, 2013; *Zhang et al.*, 2010; *Cheng et al.*, 2013; *Park et al.*, 2007].

3. Results

3.1. Wildfire Season of 2007

The summer of 2007 was the first wildfire season analyzed for wildfire contributions toward SLC. Western U.S. wildfires emitted a total of 76 Tg of CO_2 and 5.6 Tg of CO which exceeded the 2004–2008 season average of 44 Tg of CO_2 and 3.1 Tg of CO, according to the updated version of WFEI. The majority of the emissions

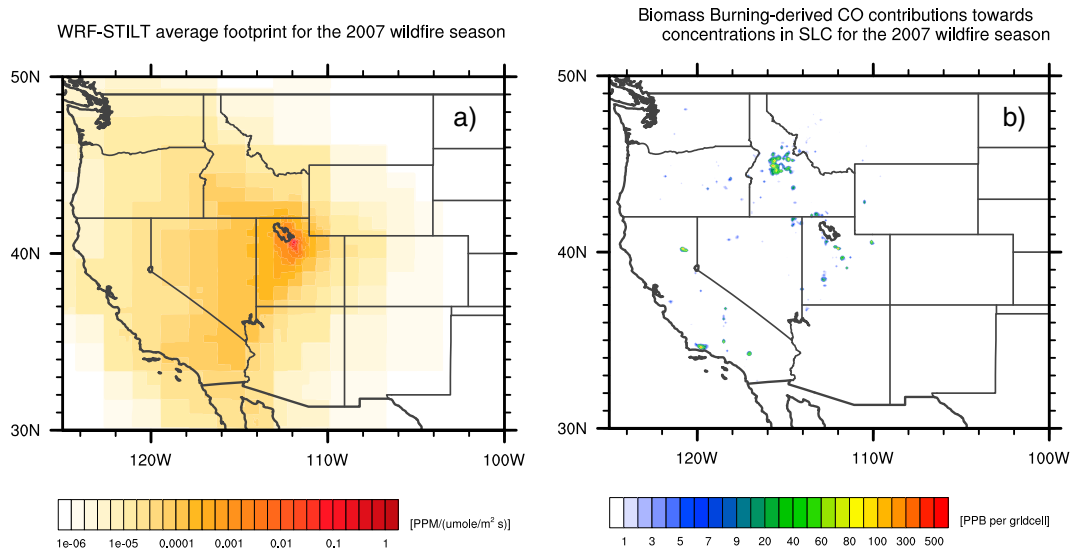

Figure 8. (a) STILT-generated average footprints for the 2007 wildfire season. (b) Wildfire-derived contributions to CO concentrations at SLC, integrated over the 2007 wildfire season.

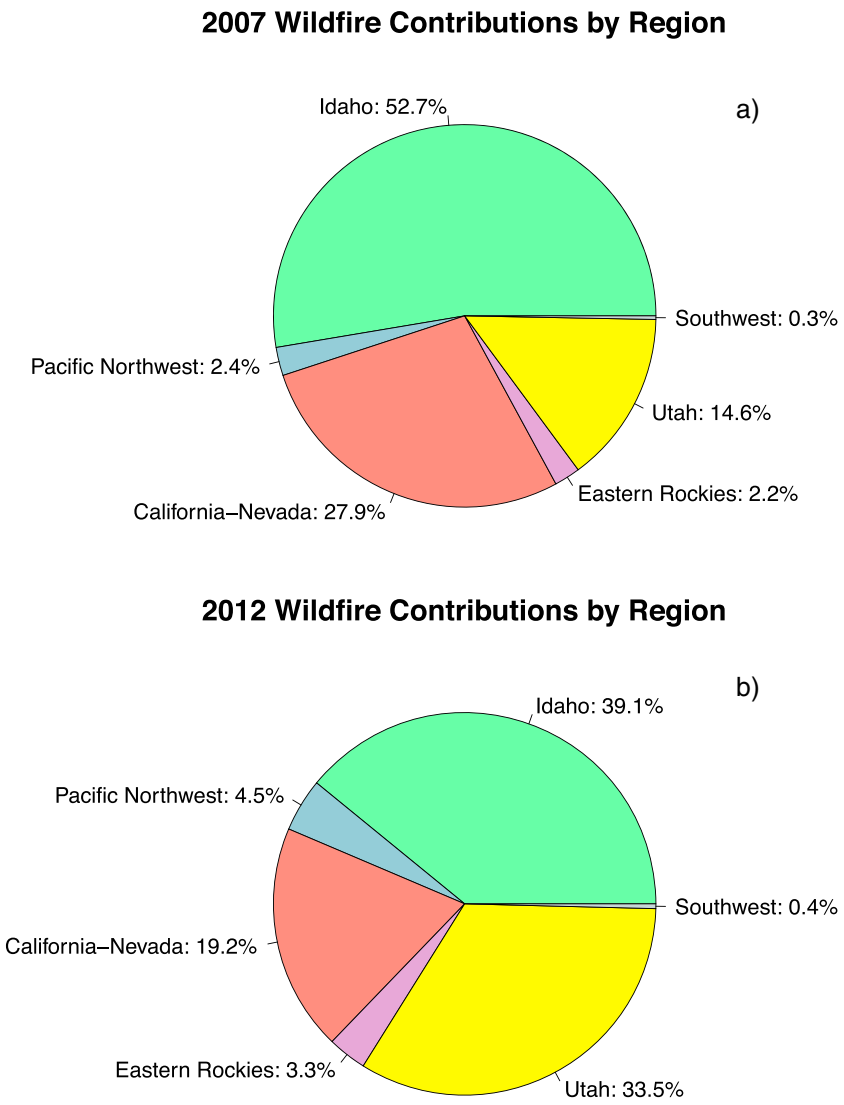

Figure 9. The contribution from each of the source regions to wildfire-derived CO enhancements at SLC for the (a) 2007 and (b) 2012 western U.S. wildfire seasons.

forthe 2007 wildfire season occurred in central Idaho, upwind of SLC (Figure 5a). A large portion of this wildfire activity occurred during the months of August and September.

Simulations for CO and CO_2 were carried out from June through October to determine the influences that upwind wildfires had on SLC air quality. STILT-simulated CO concentrations for SLC showed reasonable agreement with the measured values as the timing and magnitude of the diurnal cycle were well captured by the model (Figures 6a and 6b). Anthropogenic emissions were the dominant source of CO for SLC when integrated across the months of August and September. Northern Utah accounted for the majority (95–97%) of the anthropogenic contributions to SLC with sources outside of the state accounting for only 3–5%. Despite the significant wildfire activity across northern Idaho, the overall impact of these fire emissions on the SLC's CO concentrations was limited to a few days during the fourth week of August and third week of September (Figures 6a and 6b). Minimal wildfire contributions were observed in the modeled CO concentrations during June, July, and October (not shown).

Significant wildfire contributions toward elevated 3-hourly CO concentrations in SLC were sporadic for the 2007 western U.S. wildfire season (Figure 7a). Only a handful of these episodes contributed more than 50 ppb toward hourly CO concentrations. The mean of the "nonnegligible" wildfire episodes (defined as

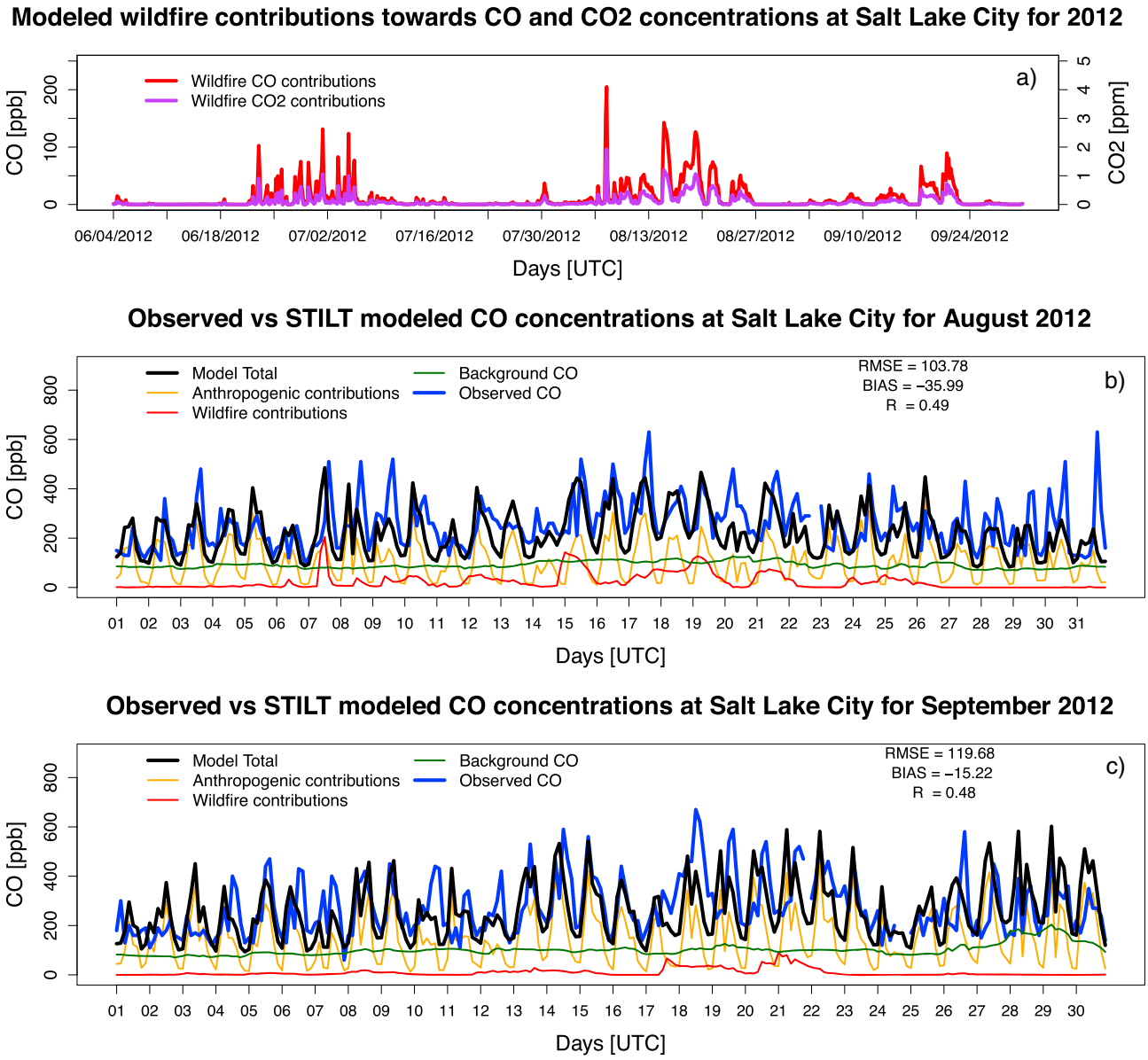

Figure 10. (a) Modeled wildfire CO contributions for the entire 2012 western U.S. wildfire season. (b and c) STILT-simulated and observed CO concentrations for SLC, zoomed in on August and September 2012. The black line is model total while the orange, red, and dark green lines are contributions from anthropogenic and fire emissions and the background CO, respectively. The blue line is the observed CO concentrations for SLC.

enhancements ≥ 5 ppb) was 23.4 ppb, while the median was much lower at 12.6 ppb. Major episodic wildfire events (>95% percentile) for the 2007 wildfire season elevated SLC's CO concentrations in excess of 86.4 ppb, with a median of 118.9 ppb.

The spatial distribution of these contributions suggested that wildfires in northern Idaho were responsible for much of the wildfire-derived CO enhancements in SLC (Figure 8). CO contributions from wildfires were aggregated by source region, as seen in Figure 8, which included the Pacific Northwest (Washington and Oregon), California + Nevada, Idaho, Utah, the Southwest (Arizona and New Mexico), and the eastern Rockies (Colorado, Wyoming, and Montana). Overall, the majority of the wildfire source contributions toward CO enhancements in SLC for 2007 came from Idaho (52.7%), with California + Nevada contributing an additional 27.9% (Figure 9a). Wildfires within Utah only contributed 14.6%, while the Southwest and the eastern Rockies had wildfire source contributions that were under 3% (Figure 9a). The Pacific Northwest contributed the remaining 2.4%.

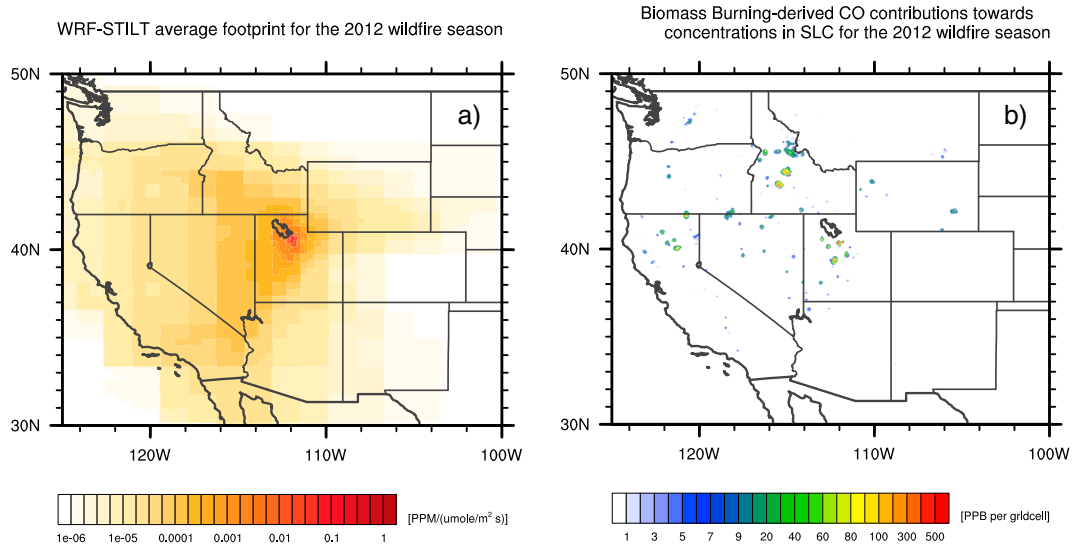

Figure 11. The same plots as in Figure 8 but for the 2012 western U.S. wildfire season.

CO_2 emitted by wildfires had a much smaller impact on SLC, as seen in Figures 6c and 6d. As with CO, the anthropogenic emissions coupled with the shallow nocturnal PBL were the strongest driver of CO_2 enhancements. Overall, wildfires played a negligible role throughout August and September (Figures 6c and 6d) despite the increased wildfire activity during 24–26 August and 6–12 September as seen in the STILT CO simulations. Anthropogenic emissions in SLC were the dominant contributor to local elevated CO_2 concentrations, with biospheric fluxes having a second-order effect. WRF-STILT CO_2 simulations were in reasonable agreement with observations. The SLC CO_2 simulations had a bias of only −1.3 ppm and a RMSE of ~11 ppm (Figures 6c and 6d). This improves upon previous WRF-STILT studies for the SLC valley [*Nehrkorn et al*., 2013; *McKain et al*., 2012], which found that the model generally underestimated CO_2 concentrations during the night. The difference here may be the enhanced capability of WRF in resolving the nocturnal inversion better (Figure 3a).

Taken as a whole, the CO_2 simulations suggest that the WRF-STILT model is performing reasonably, albeit the comparisons did not necessarily provide an indication of whether wildfire-derived CO_2 was captured by the model, due to its minor impact on elevating CO_2 values.

3.2. Wildfire Season of 2012

The 2012 wildfire season was another active year for the western U.S., with over 6 Tg of CO and 80 Tg of CO_2 emitted, according to the updated WFEI. This was nearly double the average emission for the 2004–2008 wildfire seasons over western U.S. Similar to the 2007 western U.S. wildfire season, the 2012 fires were primarily located across Idaho with additional wildfire activity located across the eastern Rockies (Figure 5b). There was also increased local wildfire activity within Utah that was absent in 2007. Simulations for the 2012 wildfire season were carried out for June through September. October 2012 was excluded from consideration since no major wildfires were present. Simulations for the 2012 wildfire season showed frequent wildfire impact on CO concentrations at SLC (Figure 10a). There were three distinct episodes of prolonged wildfire impacts: 24 June to 5 July, 6–24 August, and 19–24 September (Figure 10a). Wildfire contributions toward CO_2 concentrations in SLC were also observed during these times (Figure 10a), though these contributions were insignificant ($<$2 ppm) when changes in CO_2 concentrations in SLC generally exceed 35 ppm from local anthropogenic and biospheric sources.

The time-integrated wildfire contribution toward CO enhancement in SLC was greater in 2012 than in 2007 by a factor of 2.3. The 2012 wildfire season was characterized by more frequent episodes of wildfire-derived enhancements that often lasted longer than those in 2007 (Figure 7b). The mean CO enhancement from nonnegligible episodes ($\geq$5 ppb) was 28.6 ppb, with a median of 17.2 ppb. This was greater than the 2007

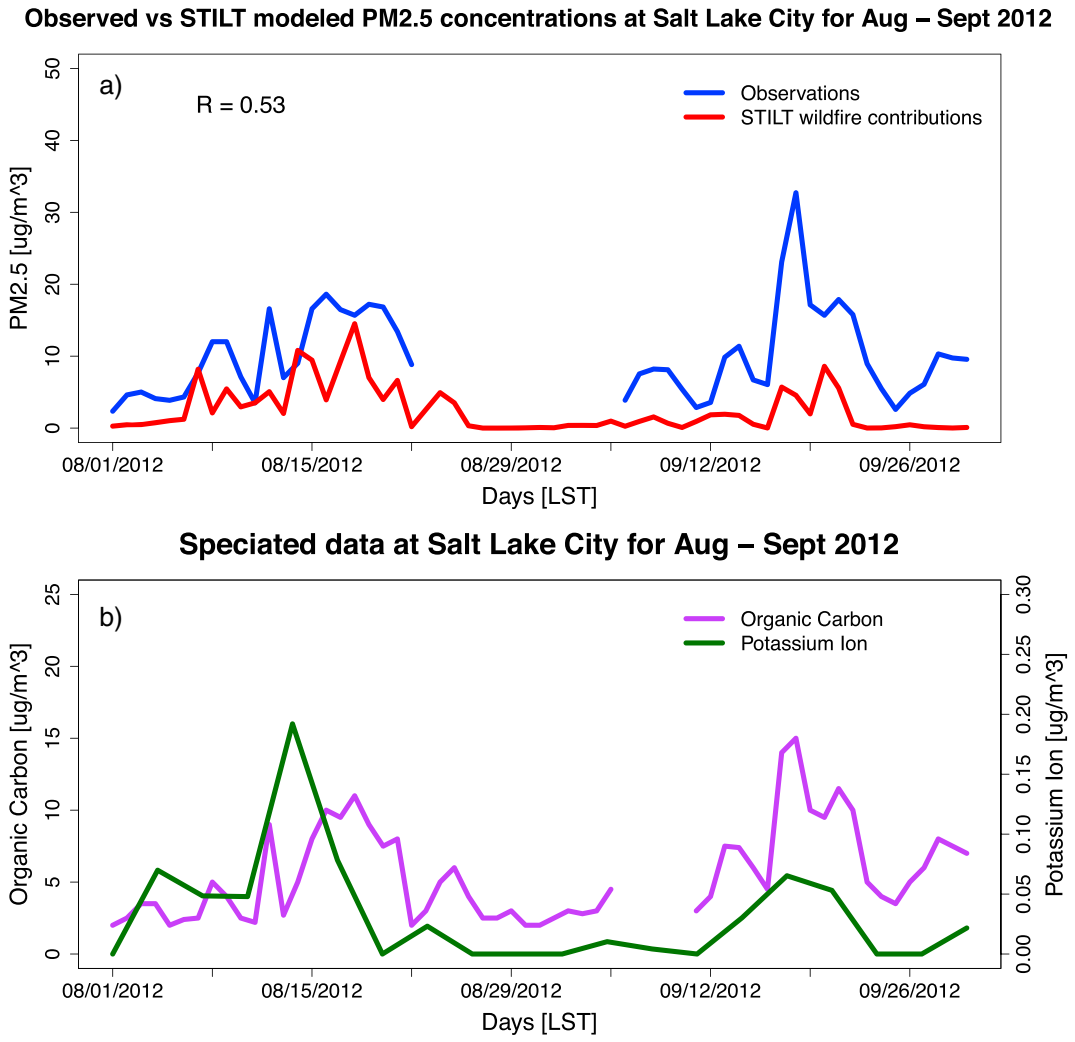

Figure 12. (a) Modeled and observed daily averaged $PM_{2.5}$ concentrations at SLC. (b) Measured values of organic carbon (daily) and speciated potassium ion concentrations (every 3 days) at SLC.

western U.S. wildfire season, which reported a mean and median of 23.4 and 12.6 ppb, respectively. The most intense wildfire episodes (>95% percentile) had enhancements with a median of 122.3 ppb (Figure 7b), which was also higher than the value in 2007.

Wildfires in Utah had a much larger impact on SLC in 2012 than in 2007, contributing 33.5% of the CO enhancements over the entire season (Figures 9b and 11), versus only 14.6% in 2007 (Figure 9a). Wildfires in Idaho continued to play a large role, with 39.1% of the contributions coming from this source region in 2012 (Figure 9b). Contributions from California + Nevada were moderate role (19.2%) while the impacts from the wildfires in the Pacific Northwest and eastern Rockies were minimal, with only 4.5% and 3.3%, respectively (Figure 9b). Contributions from the southwestern U.S. were considered negligible, with contributions under 1%.

WRF-STILT simulations for CO performed reasonably well when compared against observed values in SLC for August and September (Figures 10b and 10c). Increased wildfire activity started around 6 August and was fairly persistent through 25 August (Figures 10a and 10b). The daily averaged $PM_{2.5}$ concentrations (both modeled and observed) are shown in Figure 12a for SLC. The enhancements seen in the observed $PM_{2.5}$ correspond roughly with increases in modeled wildfire contributions to $PM_{2.5}$, with a correlation coefficient of 0.53 (Figure 12a).

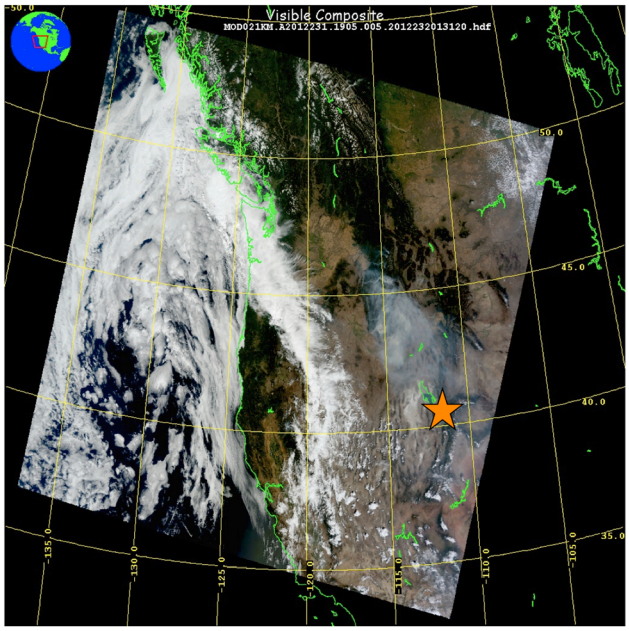

Figure 13. MODIS scan from the TERRA polar-orbiting satellite of the visible light spectrum on 18 August 2012 at 1905 UTC. The star indicates the location of SLC. Credit: NASA.

While the WRF-STILT model appeared reasonable in resolving periods of increased wildfire contributions for August and September 2012, it is difficult to determine from CO and $PM_{2.5}$ concentrations alone whether enhancements can be directly attributed to increased wildfire contributions. Therefore, speciated particulate matter observations were used as an additional means to verify days of wildfire contributions.

The increased wildfire contributions as suggested by WRF-STILT match up, in general, with the elevated concentrations of speciated organic carbon and potassium ions (Figure 12b) between 8–25 August and for 13–23 September. The correspondence between modeled $PM_{2.5}$ from wildfires against the observed $PM_{2.5}$, organic carbon, and potassium ions suggests that modeled wildfire contributions are likely realistic. However, the exact contributions suggested by the WRF-STILT to enhancements of $PM_{2.5}$ cannot be regarded as quantitative, due to the lack of consideration of chemical reactions that affect $PM_{2.5}$. This could also explain the discrepancies between the modeled wildfire contributions and the observed $PM_{2.5}$ contributions.

NASA satellite remote sensing products were also used to verify periods of increased wildfire contributions. The strongest and most persistent wildfire activity found in the WRF-STILT simulations occurred from 14 through 21 August. The MODIS Terra polar-orbiting satellite made a direct pass over western U.S. on 18 August at 1905 UTC (Figure 13). Large wildfires were present over central Idaho during this time, with smoke advected in a southward direction toward SLC (Figure 13). The aerosol optical depth (AOD) product was also available for this time (Figure 14). A higher AOD indicates that more aerosols are present in the atmospheric column [*Schaap et al.*, 2009; *Natunen et al.*, 2010; *UDAQ*, 2013]. Widespread areas across the Intermountain West with high AOD (>0.4) are colocated with the wildfires and smoke shown in Figure 13. While SLC is in a region of missing data, surrounding and upwind regions have AOD values that exceed 0.5. The cause of the missing data to the west of SLC can likely be attributed to the nearby Salt Flats. The nearest available data point to SLC was located over Ogden, UT. This point had an AOD of 0.6 (Figure 14), which loosely corresponds with a $PM_{2.5}$ mass

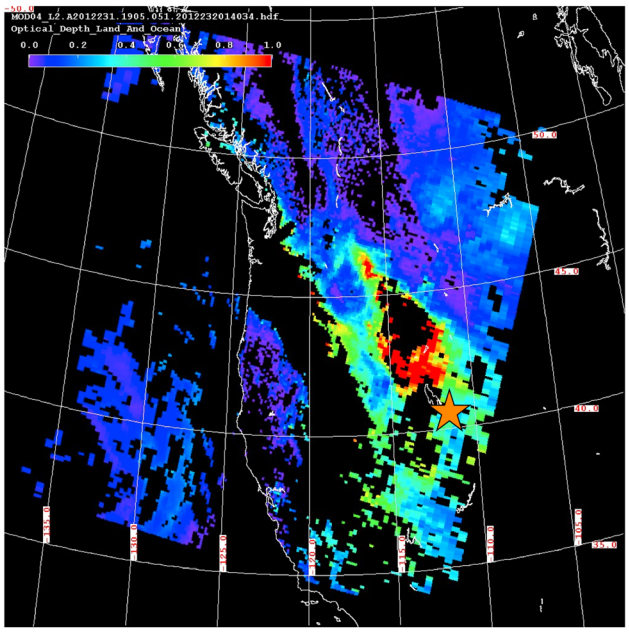

Figure 14. Aerosol optical depth as retrieved from MODIS-TERRA, observed at the same time as shown in Figure 12. The star indicates the location of SLC. Credit: NASA.

concentration of 36 $\mu g/m^3$ [*Schaap et al.*, 2009; *Natunen et al.*, 2010]. The SLC site measured $PM_{2.5}$ concentrations between 15 and 20 $\mu g/m^3$ for the same time while the STILT-modeled $PM_{2.5}$ wildfire contributions had a similar magnitude.

4. Discussion

The WRF-STILT model was used to estimate the impact of upwind wildfires on SLC's CO_2, CO, and $PM_{2.5}$ concentrations for two major western U.S. wildfire seasons. The modeling framework incorporated a variety of sources/sinks for each species in order to determine the wildfire contributions relative to the other sources/sinks. Through the analyses shown earlier in this study, the WRF model was able to adequately resolve the growth/decay of the PBL and the wind fields over northern Utah resulting in realistic meteorological drivers to derive the STILT backward trajectories. Additionally, the simulated CO_2 and CO values compare reasonably against observations in SLC.

WRF-STILT model results for CO_2 in 2007 indicate that wildfires play a negligible role toward enhancements in CO_2 concentrations within the SLC valley. As already shown by *Strong et al.* [2011], anthropogenic emissions were a dominant source of CO_2 with biospheric fluxes playing a minor role in CO_2 variability at SLC. The diurnally varying anthropogenic emissions, in combination with the growth and decay of the PBL in the SLC valley, were responsible for the strong diurnal cycles seen in CO_2, resulting in changes of 20–40 ppm for CO_2 that dominate over the <2 ppm maximum wildfire signal. This, combined with transport uncertainties associated with the WRF-STILT model (see below), likely makes the wildfire contribution to CO_2 difficult to separate out.

The simulations indicate that wildfire contributions to CO enhancements in SLC were also fairly minimal for the 2007 wildfire season, with the exception of a 2 day wildfire episode toward the end of August and another minor wildfire period in the middle of September. The 25 August event contributed substantial CO, such that concentrations increased by a factor of ~1.5 during the afternoon. Despite these large contributions, anthropogenic emissions during the nighttime led to the largest CO enhancements, due to trapping of these emissions by the nocturnal inversion. The 2012 wildfire season was characterized by more numerous wildfire contributions to CO within the SLC valley. There were several instances in which wildfire-derived CO enhancements actually exceeded those from anthropogenic emissions. Large contributions were especially prevalent across the months of August and September 2012. With the exception of a local fire on 6–8 August, most of the wildfire contributions during these months came from large wildfires in central Idaho, which were over 400 km away from SLC. Despite the increased wildfire contributions for the 2012 western U.S. wildfire season, these events were transient in nature.

Similar to CO_2, errors in modeled CO concentrations exist due to uncertainties in PBL mixing, advection, and background values. Uncertainties in the background CO concentrations as simulated by MOZART are approximately 15 ppb [*Emmons et al.*, 2010]. Errors due to advection for wildfire sources for CO are around 50%, while PBL mixing represents a relative uncertainty of 35%, following roughly the error statistics derived for CO_2 in *Lin and Gerbig* [2005] and *Gerbig et al.* [2008]. These error sources result in a ~60% uncertainty in the wildfire-derived CO enhancement (assuming statistical independence between different errors). It should be noted that significant effort in testing different WRF configurations centered over the SLC region and in assessing the veracity of the simulated meteorology (Table 1 and Figure 3) suggests that these uncertainties may be conservative.

Primary $PM_{2.5}$ contributions from wildfires were substantial for August and September for the 2012 wildfire season. Most of the increases in observed $PM_{2.5}$ concentrations corresponded with increased wildfire contributions, as suggested by the WRF-STILT model with the exception of a few days. Speciated data from SLC for August and September were consistent with times when wildfires were burning in the upwind source region, as identified by the model. Furthermore, remote sensing products from MODIS were also used to verify the source of increased levels of $PM_{2.5}$. The MODIS visible and aerosol optical depth products clearly showed large smoke plumes originating over central Idaho that fanned out over SLC. The WRF-STILT model output coupled with remote sensing images confirmed that western U.S. wildfires had a substantial impact on SLC's air quality during August to September 2012.

While the study makes a good first estimate of wildfire contributions toward $PM_{2.5}$ concentrations in SLC, more work needs to be done to account for the additional chemical production of $PM_{2.5}$ due to secondary

formation. Previous studies have indicated that the secondary production of $PM_{2.5}$ is sensitive to many environmental factors and can account for 20–80% of total $PM_{2.5}$ [*Zhang et al*., 2013; *Particulate Matter Science for Policy Makers*, 2003]. Future work will use the STILT-Chem model [*Wen et al*., 2012], which simulates chemical transformations along STILT—backward trajectories that will allow the model to explicitly calculate the secondary production of $PM_{2.5}$. This model can also be used to determine the contributions of wildfires to chemically active species such as O_3, which often exceed regulatory limits across the Intermountain West due to upwind wildfires [*Jaffe et al*., 2013; *Jaffe and Wigder*, 2012].

While the WRF-STILT model performed adequately in capturing the wildfire activity for the summer of 2012, it should be noted that the model assumed wildfire emissions took place at the surface and were only diluted initially within the PBL. Although this is likely a valid assumption for many cases in this study, significant wildfires dominated by crown burning are generally associated with higher heat fluxes and buoyancy, which may be able to inject smoke plumes directly into the free troposphere [*Freitas et al*., 2007; *Sessions et al*., 2011; *Lavouè et al*., 2000; *Cofer et al*., 1996; *Generoso et al*., 2007]. This is especially relevant for wildfires across Northern Canada that occur in boreal forests where crown burning is more prevalent. Future work will be needed to parameterize smoke plumes within Lagrangian particle dispersion models in order to reduce the uncertainty in simulating wildfire contributions.

SLC and other urban centers across the western U.S. will continue to be susceptible to a higher risk of wildfires in the coming years. Previous studies have shown a steady increase in wildfire frequency and intensity that is expected to continue as virtually all climate model projections indicate that warmer springs will continue to promote longer wildfire seasons due to earlier snowmelt [*Westerling et al*., 2006; *Dennison et al*., 2014]. The increased frequency and intensity of western U.S. wildfires will only increase the vulnerability of the population in this region to pollutants such as O_3 and $PM_{2.5}$ from wildfires.

While this study represents a first step toward quantifying the impact of wildfires on air quality for urban systems in the Intermountain West, additional model development is needed to reduce its uncertainties along with continued improvement in the wildfire emission inventories. Accounting for additional chemistry and fire plume rises will yield better understanding of the exact impacts of wildfires on western U.S. urban systems. In addition, a formal quantification of the uncertainties originating from the WRF-STILT model and wildfire emissions inventories will be included in a future study. We envision that the Lagrangian modeling framework represented by WRF-STILT could serve as a valuable tool for air quality managers, for understanding wildfire events that lead to pollutant levels exceeding the NAAQS and for potentially demonstrating exceptional events.

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