Dry Deposition Patterns and Short-Term Temperature Effects of Anthropogenic Black Carbon Emissions in California

Bachelor of Science Thesis

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May 2014

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INTRODUCTION

Black Carbon is the most light-absorbing component of fine particulate matter and is produced from the incomplete combustion of fossil fuels, biofuels, and biomass (US EPA, 2012). Black carbon (BC) is the most effective constituent of particulate matter, by mass, at absorbing solar radiation (US EPA, 2012). BC has a short atmospheric residence time of days to weeks and is removed by precipitation and direct deposition (Jacobson, 2010). Unlike long lived, well-mixed greenhouse gases, the location where BC is emitted has important implications in determining regional climate effects and evaluating potential snowpack loss. Although uncertainties remain in the magnitude of radiative forcing, several studies suggest that BC is a major contributor to climate change, estimated as possibly the second most important climate forcer behind carbon dioxide [Bond et al. (2013); Jacobson (2001b); Ramanathan and Carmichael (2008)].

While many studies have modeled the global radiative forcing of BC [Unger et al. (2010); Jacobson (2010); Bond et al. (2013)], or examined BC deposition over large regional areas such as the western United States (Qian et al., 2009), there is a lack of high resolution (i.e. state-scale) regional BC deposition modeling. The United States EPA released a report to Congress on black carbon that identified future research needs in: (1) the analysis of the impact of BC in snow and ice-covered regions, and (2) the comparison between global and regional models of BC’s contribution to temperature change (US EPA, 2012). Complex terrain provides further challenges in estimating depositional patterns of BC (Bond et al., 2013) and there is a poor understanding of the seasonal deposition of BC over the Sierra Nevada (Hadley et al., 2007).
To address part of this knowledge gap this study aims to estimate depositional patterns and short-term temperature effects of BC emissions at the state scale; California is a great candidate because it has both complex terrain and snow covered regions. The results of this study may aid in the estimation of snowpack loss and may be beneficial in the design of future field experiments that aim to collect more robust *in situ* albedo changes.

The structure of this paper is as follows. The background section covers information on BC formation, how it is measured, climate effects, major sources, and motivation for this study. Methods will describe the regional climate model, model initialization, and the anthropogenic emissions data. The results section presents the model output, followed by the discussion section with notable findings and suggestions for future research. Finally, the most important points are summarized in the conclusion.

**BACKGROUND**

BC is produced in flames during the combustion process of carbon based fuels (Bond et al., 2013). In scientific literature black carbon is referenced as BC, light absorbing carbon (LAC), elemental carbon (EC), and “soot;” but each has a specific definition. BC is quantified by optical methods (Chow et al. 2010), light absorbing carbon includes BC and brown carbon (US EPA 2012), EC is refractory carbon determined by physical and chemical analyses (Chow et al. 2010), and “soot” refers to a complex mixture of BC and organic carbon (OC) produced by incomplete combustion (US EPA 2012). While BC itself exhibits a strong positive radiative forcing through its absorption properties and darkening effects to surface albedo, the co-emitted OC can provide a cooling effect by scattering incoming solar radiation, thereby increasing earth’s albedo. Additional complication arises from a component within OC called brown carbon. Brown carbon
is capable of absorbing visible light, albeit much weaker and at specific wavelengths, which help distinguish it from BC (Bond et al., 2013). Active research in the modeling community strives to include light absorption from brown carbon, as very few modeling studies currently consider its contribution (Jacobson, 2001a). While beyond the scope of this study, it is important to note the effects of co-emitted species and consider them in future analyses to obtain better regional estimates of the net climate effect of carbonaceous aerosols. BC is the only component of carbonaceous aerosols that is considered here.

The most commonly field deployed method of estimating black carbon is a filter-based measurement of EC (US EPA 2012). In this study we use elemental carbon (EC) as a proxy for BC. Although closely related, EC and BC are not measured in the same manner and measurement error becomes more significant at higher OC:BC ratios (Chow et al., 2001). To remain consistent with the literature (Ramanathan, 2013), the terms BC and EC are used interchangeably.

BC describes solid particles of close-to-pure carbon and affects the climate through: (1) absorption of all wavelengths of radiation present in the troposphere (US EPA, 2012) and re-emitting thermal-infrared radiation to adjacent air molecules (Jacobson, 2004); (2) acceleration of snow and ice melt by reducing surface albedo and contributing to snowpack loss (Qian et al., 2009); and (3) an indirect forcing on cloud formation and precipitation patterns (US EPA, 2012). Figure 1 shows a brief summary of the primary BC climate effects.
The major sources of BC in California are wildfires, prescribed agricultural burning, and heavy-duty diesel trucks (semi-trucks) in the transportation sector (Figure 2). These three sources accounted for 55% of California’s total BC emissions in 2010. This study will focus on anthropogenic emissions of BC because higher OC:BC ratios, produced by most biomass burning, are subject to more error in the elemental carbon-based measurement network of California. Figure 2 suggests that important contributors of BC emissions in the transportation sector are semi-trucks and off-road equipment (comprised of construction, mining, logging equipment, etc.). Therefore, when considering these anthropogenic sources of BC a primary concern, and my expectation for the outcome of this study, are possible deposition areas near major transportation routes of California (interstate highway 5, among others). It is important to recognize that since 1989, California has substantially reduced atmospheric concentrations of BC (50% from 1989 to 2008) by imposing stricter emission standards for PM$_{2.5}$ from diesel combustion (Ramanathan, 2013).

The motivation for this study is the assumption that under certain meteorological conditions, BC may be deposited into the Sierra Nevada snowpack. As a crucial source of freshwater for a significant agriculture economy and major urban/suburban areas (Hadley et al., 2010), understanding the potential for this phenomena to occur is imperative for water resource management. In addition, characterizing the depositional patterns of BC provides insight for future field studies that wish to quantify the albedo reduction due to the presence of BC in California’s snowpack.
METHODS

It is difficult to produce reasonable estimates of BC’s depositional patterns with limited observational data and financial constraints for deploying short-term field equipment. The short atmospheric residence time of BC also provides challenges in quantifying the local climatic impact because BC will not be well-mixed in the hemisphere in which it was emitted (Sarofim, 2010). As such, this study will use a regional climate model capable of including BC emissions to identify regions where deposition may occur and assess the short-term temperature impacts.

This section describes the: (1) model and initialization, (2) anthropogenic emissions data – including point and area sources and the daily EC emissions that are input into the model, (3) aerosol module selected to represent the particle size distribution and radiative feedbacks, and (4) model modifications to calculate the dry deposition of BC.

WRF-Chem Model

To estimate the effects of BC and its complex feedbacks, it is advantageous to use a fully coupled meteorology-chemistry model (Zhang et al., 2010). Our regional modeling efforts use the NCAR/NOAA Weather Research and Forecasting Model with Chemistry\(^1\) (WRF-Chem) (version 3.5.1.). Previous air quality models have treated chemical processes independently of meteorological processes, which can lead to a loss of information about interactions between the two (Grell et al., 2005). This is especially important when analyzing atmospheric constituents such as BC, which can affect the radiation budget, cloud formation, and alter precipitation

\(^1\) http://ruc.noaa.gov/wrf/WG11/
patterns. Therefore, the WRF-Chem model is an appropriate choice based on the objectives of the study.

The model domain covers almost all of California, with an excluded portion residing in the southeast corner of the state (Figure 3). To provide a balance between capturing detail and computation time, the horizontal resolution is set to 8 km (Figure 3). There are 40 vertical levels that begin at sea level and reach a maximum of 20 km at the top of the model. In general, the vertical model layers follow terrain height and are compressed together near the surface, the distance between model layers increases as you approach the top of the model (Figure 4).

The boundary and initial climatological conditions, for all simulations in this study, are specified every 6 hours using Global Forecast System (GFS) analysis data\(^2\) at 0.5° latitude/longitude resolution. Background concentrations of EC, as a mixing (mass) ratio, are initialized at 1 × 10\(^{-16}\) µg/m\(^3\) throughout the 3d domain; which becomes 1.2 × 10\(^{-16}\) µg/m\(^3\) at the top of the Sierra Nevada, and ultimately reaches 1.1 × 10\(^{-15}\) µg/m\(^3\) at the top of the model (~50mb or 19.5 km) because air density decreases with increasing elevation.

*Anthropogenic Emissions of Black Carbon*

Following the methodology provided in the WRF-Chem emissions guide\(^3\) we construct the emissions data for our domain using the U.S. EPA National Emissions Inventory (NEI) for 2005. There are three primary reasons for using this particular dataset. First, this inventory is ideal because it provides “model ready” emissions data, meaning the data is provided in 24-hourly

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\(^2\) [http://nomads.ncdc.noaa.gov/data.php#hires_weather_datasets](http://nomads.ncdc.noaa.gov/data.php#hires_weather_datasets)

averaged emission rates which are required for WRF-Chem modeling. Second, the emissions data includes important emissions processing software (emiss_v03.F and convert_emiss.F) which converts the raw data into a format the model can interpret and grid accordingly. Third, despite its national extent this dataset has adequate spatial resolution with area averaged emissions spaced 4 km horizontally.

The NEI 2005 dataset includes anthropogenic emissions for 41 speciated volatile organic compounds, 7 primary species, and 5 speciated PM$_{2.5}$ aerosols which include elemental carbon. All wildfire and prescribed burning emissions were removed from the dataset, and while these are significant sources of BC, the omission is preferable because year-specific fire emissions can heavily bias the depositional patterns in the model results (Qian et al, 2009). In addition, the radiative forcing and quantity of emissions from biomass sources has greater uncertainty because the burning behavior determines the quantity of emitted BC (Bond et al., 2013). It is important to note that the emissions dataset is a repeating diurnal cycle representing a typical summer day (in July), when elemental carbon concentrations are at a minimum (Ramanathan et al., 2013). Therefore, simulations with NEI 2005 emissions data represent a lower bound estimate.

*Point Sources*

Point sources are primarily factories, power plants, and other stationary sources. The NEI 2005 dataset provides other important attributes for each point source that are necessary for the emissions processing software to prepare for injection into the model domain. These attributes include the smokestack height, diameter, and flow velocity.
The point emissions are gridded onto the model domain and then converted from emission rates (tons/hr) into a flux by dividing by the model grid cell area. The emiss_v03.F subroutine then determines which model grid layer the stack resides in, and obtains the wind speed from the climatology initialization data at the model grid cell above the stack (Figure 4). Next, the subroutine determines the thickness of the emissions injection layer \( L_e \), which is calculated by the following equation:

\[
L_e = \frac{3 \times \text{Stack Diameter} \times \text{Stack Height}}{\text{wind speed above stack}}
\]

Should the injection layer span across multiple model grid cells, the flux is partitioned into fractional values based on the coverage of the injection layer (Figure 4).

**Area Sources**

Area sources are predominantly transportation-related emissions and the process for adding them into model is fairly straightforward. The emiss_v03.F subroutine simply transfers the 4 km emission grid cells from the raw dataset into the corresponding location on our 8 km model grid, at the lowest grid cell (Figure 5). It is unclear how the subroutine allocates emission grid cells (4 km) that may overlap multiple model grid cells (8 km) in the transfer process; we assume that majority coverage determines which grid cell the area emissions are added into.

**Daily EC Emissions Input into the Model**

Figure 6 shows the NEI 2005 daily emission of EC inputted into the model, for each day of the simulation period. As expected, high EC emissions are found in urban areas and major transportation routes (Figure 6).
Aerosol Module

With the support of the WRF-Chem user guide\(^4\), the chemistry mechanism selected for this study is the regional acid deposition model 2\(^{nd}\) generation (RADM2)\(^5\). This mechanism is most commonly used with the aerosol module selected for the study, which is described below. RADM2 designates the conversion table which is used to convert the raw anthropogenic emissions to a WRF-Chem variable name. Refer to Stockwell et al. (1990) for additional details about RADM2.

The aerosol module determines the size distribution and particle number of aerosol emissions, which is important because these attributes can affect radiative transfer and cloud interactions. There are three types of aerosol modules available in WRF-Chem: bulk, bin, and modal. The bulk aerosol module (GOCART) is numerically efficient but difficult to couple with radiation and cloud processes. MOSAIC is an example of a bin module, which assigns the mass of BC into different bin sizes (from 39 nm to 10 \(\mu\)m). While the MOSAIC scheme is described as the “most modern” aerosol scheme in WRF-Chem it is also more computationally demanding by a factor of 2 or more. For these reasons this study uses a modal aerosol module.

The modal aerosol dynamics module for Europe (MADE) is coupled with the secondary organic aerosol model (SORGAM), hereafter MADE/SORGAM. This aerosol scheme distributes the size of BC particles based on two log-normal aerosol modes (three modes for most aerosols – BC particles only occupy the smaller modes) (Figure 7). MADE/SORGAM assumes each mode size is internally mixed, meaning all BC particles within the same mode size have the same chemical

\[^5\] http://ruc.noaa.gov/wrf/WG11/radm2.htm
composition (Zhao et al., 2011). MADE/SORGAM also accounts for the unique optical properties of each aerosol type, including extinction, single-scattering albedo, and asymmetry factors, among others (Zhao et al., 2011). A comprehensive overview of the MADE/SORGAM scheme is provided in Grell et al., (2005) and the references therein. Due to technical difficulties, this study was not able to include aqueous chemical reactions in the MADE/SORGAM scheme, therefore, wet deposition (scavenging) and cloud chemistry processes are not represented here.

*Modifications to WRF-Chem: Calculating BC Dry Deposition*

Before discovering the deposition velocity array and how to include this information in the final model output, Dr. Dave Dempsey modified part of the WRF-Chem code. Following an example from other WRF-Chem users\(^6\), Dr. Dempsey modified the deposition module (dry_dep_driver.F) to store accumulated BC dry deposition values into an unused array; registry changes allowed this array to be displayed as an output field.

In the model, BC experiences: (1) advection, (2) vertical mixing, (3) settling, and (4) vertical emission flux divergence (Figure 5). These processes are calculated separately at each time step, with the exception of items (2) and (3) above, which are calculated together. To determine when BC is deposited onto the surface, the mass of BC in each column (Figure 5) is calculated, and any loss between time steps that is not due to one of the four processes above (the exception is settling at the lowest grid layer), must have been deposited at the lowest model grid cell in that column. Figure 8 shows the validation of our deposition method compared to the estimate derived from deposition velocity, using the model output from the longest model run in this study (~ 2 week simulation). Our method compares well against the method derived from deposition velocity, the largest difference (105 \(\mu g/m^2\)) indicating an overestimate by our

\(^6\) [http://aqmeii-eu.wikidot.com/models:wrf-chem-ncar#toc5](http://aqmeii-eu.wikidot.com/models:wrf-chem-ncar#toc5)
method) occurs east of Bakersfield in Southern California (Figure 8). The results of the 2 week simulation will show that these overestimates are not significant (3% reduction in the location of maximum deposition between our method and deposition velocity) and are within the bounds of uncertainty for any modeling result, therefore, the results presented below use our BC deposition method.

RESULTS

Three model runs are presented here. The first is a 2 week case study in the winter of 2013-2014; the second is a 3.5 day simulation in November 2013, and the last is a 4 day run in February-March 2014. For each case study a description of the meteorological conditions will be followed by the observed BC deposition patterns and temperature anomalies. The output of all model runs is provided in 3 hour increments. Hyperlinks (see footnotes) are provided to view videos (.mov files) of the model output for each case study. Temperature anomaly videos were created by subtracting the temperature at 2 m above the surface in the baseline run (WRF with no emissions and chemistry) from the WRF-Chem run. It is important to note that the temperature anomaly videos do not represent BC only, as other emissions in our dataset affect the radiative forcing.

December Case Study: calm to light winds

This time period has ideal meteorological conditions for dry deposition, no precipitation and calm to light surface winds. The 2 week simulation from December 23, 2013 – January 6, 2014 stopped 15 hours short of a full 14-day period. Figure 9 shows the accumulated BC dry deposition after 2 weeks; the maximum is approximately 3,260 μg/m² along the ridges of transitional mountain ranges between the southern Sierra Nevada and the Tehachapi Mountains.
BC tends to accumulate in areas of elevated topography (Figures 10a and 10b), driven by downslope winds in most locations. Southern California produces high BC emissions which appear as visible “clouds” (EC isosurfaces of 0.1 μg/kg) that linger near the surface and promote deposition. The BC isosurface represents a mixing (mass) ratio that appears as a “cloud,” where values are higher than 0.1 μg/kg inside the isosurface, and lower outside of the isosurface. Winds at 10 m above the surface seem to most strongly influence BC isosurfaces and the rate at which they diffuse and are transported away from the source region.

In the temperature anomaly video, the time stamps reflect UTC dates and times, the following descriptions are converted to PST. For clarity, temperature anomalies between ±1°C are transparent; positive values indicate a warming forcing from the presence of emissions and negative indicates cooling. The maximum temperature anomaly of 6°C occurs on the north side of the Sierra Nevada at 4 pm PST on December 27th. On the same day, beginning at 10 am PST, the surface temperature increases 1-3°C across most of northern and central California, and moves southward and disappears around 4 pm PST on December 28th. These anomalies do not seem to correlate with areas of high BC emissions (Figure 6) or show a consistent diurnal signal. The Sierra Nevada, where temperature change is particularly important, experiences a 3-4°C increase from 4pm on Dec 30th to 7 am on Dec 31st due to the presence of anthropogenic emissions.

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7 http://virga.sfsu.edu/data/wrf/videos/DecCase_BCDwnSlopeDep_10mWinds_oblique.mov
8 http://virga.sfsu.edu/data/wrf/videos/DecCase_BCdep_isosfc_oblique.mov
9 http://virga.sfsu.edu/data/wrf/videos/DecCase_BCdep_isosfc_10mWinds_plan.mov
10 http://virga.sfsu.edu/data/wrf/videos/DecCase_TempAnomaly_TransparentFromPlusOrMinus1.mov
**November Case Study: offshore winds**

A 3.5 day simulation from November 19 – 23, 2013 was selected to investigate how depositional patterns may change due to meteorological conditions; the winds at 10 m above the surface shift to a prominent offshore pattern halfway through the model run\(^1\). Figure 11 shows the accumulated dry deposition of BC after 3.5 days. Similar to the December case, the deposition hotspot occurred in the mountains at the southeast portion of the Central Valley, with a maximum value of approximately 775 µg/m\(^2\) (Figure 11). BC deposition is most common along ridges of elevated terrain (Figures 12a and 12b). High sources of BC create “clouds” (EC isosurface of 0.1 µg/kg) that remain in the source area and promote deposition\(^12\).

The temperature anomaly video\(^13\) from this simulation shows a scattered pattern of temperature variability (±1°C are transparent), with the maximum anomaly (8.7°C) located in the northern Sierra Nevada at 4 am PST on November 21\(^{st}\). Of particular interest is the 5-8°C temperature difference along the Sierra Nevada at 1 am and 4 am PST on November 23\(^{rd}\). Similar to the December case, the anomalies do not correlate with areas of high BC emissions (Figure 6) or show a consistent diurnal signal.

**February Case Study: onshore winds**

The 4 day simulation from February 25 – March 2, 2014 displays an onshore wind (10 m above the surface) pattern with an approaching storm off the central California coast in the final day\(^14\).

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\(^1\) [http://virga.sfsu.edu/data/wrf/videos/NovCase_BCdep_isosfc_10mWinds_planview.mov](http://virga.sfsu.edu/data/wrf/videos/NovCase_BCdep_isosfc_10mWinds_planview.mov)

\(^2\) [http://virga.sfsu.edu/data/wrf/videos/NovCase_BCdep_isosfc_oblique.mov](http://virga.sfsu.edu/data/wrf/videos/NovCase_BCdep_isosfc_oblique.mov)

\(^3\) [http://virga.sfsu.edu/data/wrf/videos/NovCase_TempAnomaly_TransparentFromPlusOrMinus1.mov](http://virga.sfsu.edu/data/wrf/videos/NovCase_TempAnomaly_TransparentFromPlusOrMinus1.mov)

\(^4\) [http://virga.sfsu.edu/data/wrf/videos/FebCase_BCdep_isosfc_10mWinds_plan.mov](http://virga.sfsu.edu/data/wrf/videos/FebCase_BCdep_isosfc_10mWinds_plan.mov)
Figure 13 shows the accumulated BC dry deposition after 4 days. Like the other case studies, the depositional hotspot continues to develop in the mountains along the southeast end of the Central Valley, with a maximum deposition value of approximately 780 μg/m² (Figure 13). Again, BC deposition is most common along ridges of elevated terrain (Figure 14). The BC isosurfaces (0.1 μg/kg) in southern California are advected to the northeast, eventually depositing (from 30 – 100 μg/m²) across a wide area, including parts of Nevada.

The temperature anomaly video reveals a similar scattered pattern (±1°C are transparent) as the November case. The maximum anomaly (7.5°C) occurs in southern Sierra Nevada at 7 pm PST on February 27th. There is a weak diurnal signal with cooling during the day and mild warming at night, but no correlation to areas of high BC emissions (Figure 6).

**DISCUSSION**

The short-term temperature effects were not successfully analyzed in this work, requiring additional simulations with further modification to isolate BC; because BC is not solely represented and could not be correlated to high emission sources or a consistent diurnal pattern, they will not be discussed further. Refer to Ramanathan (2013) for a comprehensive review of the radiative forcing of BC in California.

It is important to emphasize that our model results demonstrate the particular meteorological conditions that may be favorable for BC dry deposition. More simulations are required to adequately predict long-term deposition patterns across California and should be constrained by

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15 [http://virga.sfsu.edu/data/wrf/videos/FebCase_BCdep_isosfc_10mWinds_plan.mov](http://virga.sfsu.edu/data/wrf/videos/FebCase_BCdep_isosfc_10mWinds_plan.mov)
16 [http://virga.sfsu.edu/data/wrf/videos/FebCase_TempAnomaly_TransparentFromPlusOrMinus1.mov](http://virga.sfsu.edu/data/wrf/videos/FebCase_TempAnomaly_TransparentFromPlusOrMinus1.mov)
observational data. This section will describe the major findings and potential implications for the patterns observed, followed by suggestions for future work.

**Major findings**

The expectation of dry deposition occurring near major transportation routes was not conclusively answered by the short-term simulations of this study. However, the results suggest that BC dry deposition is most likely to occur along ridges of elevated terrain and is enhanced by downslope winds. Periods of calm to light winds increase deposition near BC sources and all case studies show maximum deposition along the ridges of the transitional mountain range between the Tehachapi Mountains and the southern Sierra Nevada (Figures 9, 11, and 13). The San Joaquín Valley has some of the worst air quality in the nation, where PM$_{2.5}$ (a component of which is BC) repeatedly fails to meet federal health standards$^{17}$. Therefore, it seems reasonable that the model results show high BC deposition at the southern end of the valley, where air pollutants are confined by the surrounding elevated topography. There is an unexpected secondary deposition hotspot in the northeast corner of Shasta County (Figure 10a), where BC accumulates in a valley of elevated terrain during downslope wind conditions. The BC source in Shasta County is not clear and the deposition which occurs in an elevated valley (~1,000m a.s.l.) seems to counter the common trend of deposition along ridges. The accuracy of these predicted patterns, especially at the aforementioned locations, should be assessed with field measurements in future studies.

This study also finds that dry deposition may be possible in the Sierra Nevada under calm to light and onshore wind conditions. In our longest simulation, deposition along the windward

$^{17}$ [http://www2.epa.gov/sanjoaquinvalley/epa-activities-cleaner-air](http://www2.epa.gov/sanjoaquinvalley/epa-activities-cleaner-air)
side of the Sierra Nevada ranges from approximately $50 - 225 \mu g/m^2$. Without including wet deposition and an incomplete BC emissions dataset (i.e. no biomass sources, no transported out-of-domain emissions, etc.), it is likely that the magnitude of total deposition is much higher than this study suggests. This is of particular interest to California’s water resources because BC deposited on snow reduces surface albedo and accelerates snowmelt (Bond et al., 2013). As snow ages the ice crystals grow (Hadley et al., 2010) and amplify the light-absorbing effect of BC in the snowpack by more than a factor of three (Flanner et al., 2007). Furthermore, when melting commences some BC (hydrophobic) is left at the surface (Conway et al., 1996), increasing BC snow-surface concentrations, further reducing albedo and accelerating snowmelt (Flanner et al., 2007). The drought California is currently experiencing raises additional concern because the lack of fresh snow means BC will stay exposed at the snow surface, promoting the processes described above. The sensitivity of snowpack to BC perturbation highlights the importance of establishing long-term BC deposition patterns in the Sierra Nevada, its progression through the snowpack, and the effect on snowmelt rates.

**Suggestions for future work**

Including emissions of BC that are transported from outside of California will improve the quality of the model results. At three remote high elevation sites in Northern and Central California, the average contribution of Asian BC emissions may have been one quarter to one third of the observed BC in snowpack; this contribution will become more significant as Asian BC emissions continue to increase (Hadley et al., 2010).
INcorporating these transported BC emissions requires careful vertical placement in the model. A recent modeling study (Ramanathan, 2013) combined BC data from the ground based IMPROVE (Interagency Monitoring for Protected Visual Environments) network for values between the surface and 500 m, and from the CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation) satellite for vertical distribution of aerosols above 500 m. Data from the NASA ground based AERONET (Aerosol Robotic Network) global network which provides long-term, continuous, and readily available measurements of aerosol optical depth (Ramanathan, 2013) may also improve model estimates. These datasets may be useful for future modeling studies that wish to predict the total (wet and dry) long-term BC deposition.

The most important recommendation is to include wet deposition, as this is an extremely efficient removal mechanism for BC (Hadley et al., 2010). Employing the MOSAIC aerosol scheme in future efforts is also advised if the computation demand can be met, as this scheme is currently well supported by the WRF-Chem modeling community and includes wet deposition. Producing improved estimates of seasonal and annual deposition patterns in California is best achieved by conducting longer model runs with the MOSAIC scheme, improving the input emissions data as described above, and including wet deposition.

CONCLUSION

BC dry deposition patterns are highly dependent on meteorological conditions (especially winds) and terrain. The complex topography of California presents opportunities for locally emitted BC to accumulate in low lying valleys and eventually deposit on high terrain, especially along the ridges of the transitional mountain range between the Tehachapi Mountains and the southern
Sierra Nevada. However, these are partial results from short duration simulations where BC wet deposition and transported emissions from outside of California are not included. Even with these shortcomings, this study makes the first step towards identifying conditions that are conducive to BC dry deposition in California. The findings and recommendations may provide insight for future modeling efforts and guidance for field campaigns pursuing optimal locations for the collection of observational data.
Figure 1. Summary of the primary BC climate effects. BC (black circles) contributes to surface dimming, absorbs all wavelengths of radiation present in the troposphere, and accelerates snow and ice melt. Note: all climate effects of BC are not shown here (for all known effects refer to Bond et al., 2013).

Figure 2. California’s BC emissions in 2010, by economic sector. Wildfires and prescribed agricultural burning account for 97% of Agriculture & Forestry emissions. Diesel semi-trucks, aircraft, commercial boats, and off-road equipment account for 71% of Transportation emissions. Speciated source profiles of PM$_{2.5}$ were obtained from Chow et al., (2010) to derive BC emissions from the source (link above).
Figure 3. Domain of the WRF-Chem model. Horizontal resolution is 8 km (visible as the colored “pixels”) with 40 vertical levels from sea level to 20 km at the top of the model.
Figure 4. The emissions input process for point sources. If an injection layer covers multiple grid cells, the emission flux is partitioned (shown above with purple arrows).

\[ L_e = \frac{3 \times \text{Stack Diameter} \times \text{Stack Height}}{\text{wind speed above stack}} \]

Figure 5. The emissions input process for area sources and a visual description of BC movement within the model. Area emissions are provided in 4 km horizontal resolution and mapped to the corresponding location on the model domain, at the lowest model grid layer (gray arrow). BC can experience four things in the model: advection (purple arrows), vertical mixing (green arrows outlined in black), settling (green arrows) which can become deposition at the lowest grid layer, and vertical emission flux divergence (not shown).
Figure 6. Daily emissions of elemental carbon (particle diameters < 10 μm) from the NEI 2005 dataset, which are input into the model each day of the simulation period. Adapted from Qian et al. (2009).

Figure 7. The distribution of aerosol particle sizes in a modal aerosol scheme (MADE/SORGAM). The twin otter data (black) is from in situ aircraft measurements. BC is represented by the two smaller particle modes (blue and green) in the model. From Jan Kazil, in the WRF-Chem tutorial PowerPoint presentation, 22 July 2013.
Figure 8. Difference between our accumulated BC dry deposition method and the method derived from depositional velocity, at the end of a ~2 week simulation. For clarity, differences of ±5 $\mu g/m^2$ are transparent. Positive values indicate an overestimate by our method, while negative values indicate the opposite.
Figure 9. Accumulated dry deposition of elemental carbon after approximately 2 weeks in December 23, 2013 – January 6, 2014. For clarity, values below 50 $\mu g/m^2$ are transparent. The maximum deposition value is 3,260 $\mu g/m^2$, located in the transitional ranges between the southern Sierra Nevada and the Tehachapi Mountains.
Figure 10. Oblique views of the accumulated dry deposition of elemental carbon from Figure 9. (A) View to the north and (B) view to the southeast. BC accumulates in locations where complex terrain is encountered and is highest in the transitional ranges between the southern Sierra Nevada and the Tehachapi Mountains.
Figure 11. Accumulated dry deposition of elemental carbon after 3.5 days of simulation in November 19-23, 2013. For clarity, values below 25 μg/m² are transparent. The maximum deposition value is 775 μg/m², located in the transitional ranges between the southern Sierra Nevada and the Tehachapi Mountains.

Figure 12. Oblique views of the accumulated dry deposition of elemental carbon from Figure 11. (A) View to the north and (B) view to the southeast. Maximum BC deposition occurs in the transitional ranges between the southern Sierra Nevada and the Tehachapi Mountains.
Figure 13. Accumulated dry deposition of elemental carbon after a 4 day simulation from February 25 – March 1, 2014. For clarity, values below 25 $\mu g/m^2$ are transparent. The maximum deposition value is 780 $\mu g/m^2$, located in the transitional ranges between the southern Sierra Nevada and the Tehachapi Mountains.

Figure 14. Oblique view of the accumulated dry deposition of elemental carbon from Figure 13. Onshore winds lowered the quantity of BC deposited on the ridge hotspot and also spread BC deposition into Nevada.
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