EXPLORING THE IMPACTS OF REDUCED SNOWPACK DUE TO LIGHT-ABSORBING AEROSOLS IN SNOW, INCLUDING POTENTIAL INFLUENCE ON WILDFIRES

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ABSTRACT

The mountain snowpack is an essential resource for both the environment as well as society. Recent studies have shown light-absorbing aerosols (LAA) in snow such as desert dust and black carbon to be important players in surface energy and water budgets of mountain areas across Western United States (WUS). The presence of LAA in snow, by shifting snowmelt timing, can have an impact on soil and vegetation conditions in subsequent months. Based on historical data, strong correlations were found between snowmelt timing and wildfire activity, with the suggestion that a shorter snow season can lead to drier soil and vegetation conditions, which implies greater opportunities for wildfires. In this study, we aim to investigate the impact of a reduced snowpack and earlier snowmelt due to LAA in snow on wildfire risk across various regions of WUS, including the Cascade, Sierra Nevada, and southern Rocky Mountains. To achieve this goal, we employ a regional climate model with a physically-based snow scheme that accounts for presence of LAA in snow. By comparing the LAA-loaded and LAA-free simulations over 10 years, we explore the changes induced by LAA to the water balance, as well as potential implications to wildfires. (KEYWORDS: dust and black carbon in snow, runoff changes, regional climate modeling, western United States, hydrologic cycle, wildfire risk)

INTRODUCTION

Seasonal runoff from mountain snowpacks across the Western United States (WUS) is an essential resource to the population of this region, from drinking and irrigation to agricultural practices, hydroelectric power, and recreational use. This snowmelt also has a significant control over the hydrologic cycle and other parts of the regional and local environment, such as soil and vegetation state, which in turn can influence wildfire activity.

Recent studies have shown light-absorbing aerosols (LAA) in snow, such as desert dust and black carbon (BC), to be important players in surface energy (SEB) and water budgets (WB) of mountain areas across Western United States (WUS). In southern Rocky Mountains, CO, *in situ* measurements (Painter et al., 2012; Skiles et al., 2012) and point-based (Painter et al., 2010) and regional climate modeling (Qian et al., 2009; Oaida et al., 2015) efforts suggest dust and/or BC in snow cause a significant reduction in snow albedo that leads to excess solar radiation being absorbed at the surface, which in turn increases surface temperature, enhances snowmelt and changes runoff timing and amount. Similar impacts have also been observed on Mount Olympus, WA, where it has been suggested BC from forest fires have the potential to accelerate glacier snowmelt (Kaspari et al., 2015). In the Sierra Nevada Mountains, CA, local and trans-Pacific BC in snow has been observed (Hadley et al., 2010), with modeling studies (Qian et al., 2009) indicating its radiative forcing to have an impact on SEB and WB.

Furthermore, using historical data, Westerling et al. (2006) found strong correlations between both wildfire frequency and spring/summertime temperature, and wildfive activity and snowmelt timing, with warmer years and earlier snowmelt corresponding to increased wildfire occurance. These signals were concentrated at higher elevations, typically between 1680 and 2590 m. They suggested moisture deficit is linked to forest fire vulnerability, with ealier snowmelt leading to an ealier and longer dry season, causing more extended periods when ignition could occur, and drier soil and vegetation, all of which imply greater opportunity for wildfires.

Thus far there have been no modeling studies investigating potential links between the impacts of LAA in snow on mountain runoff and the hydrologic cycle, and their implications to wildfire activity across the WUS. In this work, we use a regional climate model with a physically-based snow scheme that was modified to account for presence of LAA in snow, to first assess the effects of LAA such as dust and BC in snow on the water budget of

Paper presented Western Snow Conference 2016

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various regions across WUS, including the Cascade, Sierra Nevada, and southern Rocky Mountains. We then explore the idea that LAA in snow, by changing springtime snowmelt timing and/or amount, can have an impact on soil and vegetation conditions in subsequent summer months, therefore affecting wildfire activity.

METHODS

To assess the impact of LAA in snow on the hydrologic cycle and potential implications to wildfire risk, we use the Weather Research and Forecasting model (WRF-ARW v3.4; Shamarock et al., 2008), as the regional climate model (RCM). WRF-ARW has been previously coupled with the Simplified Simple Biosphere (SSiB3, Xue et al., 1991; Xue et al., 2003) land surface model, and is referred to as WRF/SSiB3. For this study, a special version of the WRF/SSiB3 RCM was used, where improvements to snow radiative processes are addressed, including those due to snow aging (snow grain growth) and presence of LAA in snow. This was achieved by incorporating the SNow ICe and Aerosol Radiative (SNICAR) model by Flanner and Zender (2005, 2006) within the WRF/SSiB-3 model framework. Details on this model development can be found in Oaida et al. (2015).

The RCM model was used to run simulations for ten continuous years from 2000 to 2009 over the North American domain, with a horizontal spatial resolution of 45 km by 45 km. Shown in this presentation are select results over WUS region only (30-50°N, 125-103°W). Two sets of ten-year simulations were done, one with LAA in snow (AER) and one without LAA surface deposition (NOA), i.e. clean snow. For the AER simulations, surface aerosol deposition data from GOCART was used as forcing. GOCART, the Goddard Chemistry Aerosol Radiation and Transport model, simulates emission, transport, and wet and dry deposition of major tropospheric LAA components, including dust, BC, OC (e.g. see Ginoux et al., 2001; Chin et al., 2002). GOCART was ran separately from WRF/SSiB/aer, and its output of surface LAA was used as input for the RCM's AER scenario. By taking the difference between AER and NOA, we can see what impact dust and BC can have on the hydrologic cycle.

RESULTS & DISCUSSION

The largest source of dust across North America is in southwest US, areas like the Great Basin and Colorado Plateau. Substantial sources of BC are seen in coastal areas of WUS, where industrial and high-density population centers are located. Therefore, the mountainous areas of WUS closest to these source regions will see the largest amounts of LAA in snow (Figure 1). These include the Cascade Mountains in WA and OR, Sierra Nevada Mountains in CA, and southern Rocky Mountains in CO. LAA in snow have the largest impact during spring, when peak snow, strongest incoming solar radiation, and LAA in snow overlap the most. Focusing our results on WUS region, we observe a 9-water year (WY) mean decrease in Mar-Apr-May (MAM) snow water equivalent (SWE) of 12 mm. This is in response to an average 2% decrease in albedo, a mean 8.5 W/m^2 increase in absorbed solar radiation at the surface, and a skin temperature warming of 0.5 °C when LAA are present in snow, compared to clean snow. Given these changes in the surface energy budget and SWE, runoff increases earlier in the season, decreasing in subsequent months, indicating a shift in runoff towards an earlier date (Figure 1). For example, the southern Rockies (36-42N, 109-105W) see a change in center of mass of runoff ranging -1.5 to -6.4 days in the AER scenario, with a 9-WY mean of -3.6 days. Furthermore, certain regions experience net annual losses in runoff; Upper Colorado River Basin (UCRB) net annual runoff decreases by about 3% due to earlier snowmelt (and increased evapotranspiration, ET). In other areas, such as Sierra Nevada Mountains, temporary increases in runoff, ET, and total soil moisture content (TSMC) in the spring lead to decrease in summertime water storage; mean net annual TSMC in this region decreases by 24 mm, with a persistent loss in TSMC Jul-Sept. Unlike the UCRB region whose soils get replenished by North American monsoonal rains, disguising potential summertime impacts from LAA in snow, the Sierra Nevada soils become drier from LAA in snow effects. This is also apparent when total soil moisture content is plotted against elevation (not shown here, see poster). If fact, there is a general dependency of effects of LAA in snow with terrain height, with the largest impacts taking place at higher elevations, generally above 1500 m.

Given this notable decrease in soil moisture in the Sierra Nevada Mountains region when LAA in snow are present, especially at higher elevations, and the observational findings of Westerling et al. (2006), we investigate the impact of SEB and WB changes on wildfire risk. We develop a fire vulnerability index (FVI) based on the methods in Westerling et al. (2006), with some modifications. Here, FVI is defined as the percent difference in moisture deficit between AER and NOA scenarios, and scaled by vegetation fraction, vegfra:

$$FVI = [\ (MD_{aer} - MD_{noaer}) / (MD_{aer} + MD_{noaer})\ ] \times vegfra$$

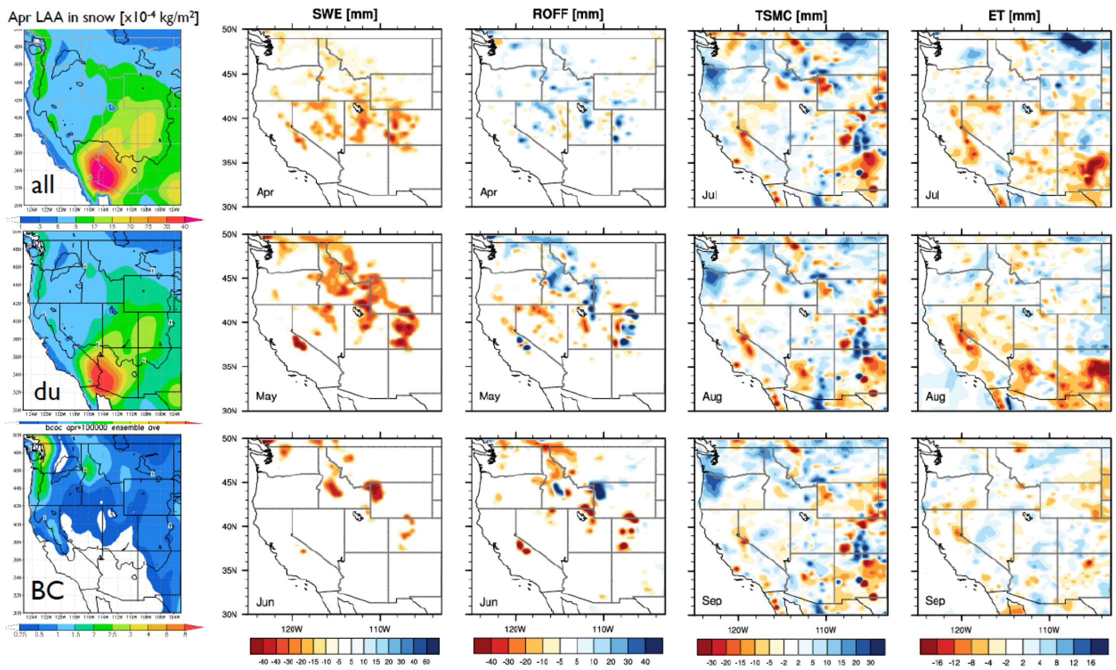

Figure 1. Spatial distribution of 9-WY mean April LAA in snow maps for all (dust+BC+OC) (top), dust (middle), and BC (bottom), and changes in Apr-May-Jun SWE and runoff, and Jul-Aug-Sept TSMC and ET [all in mm].

Moisture deficit, MD, is the difference between potential ET (modulated by temperature) and actual ET (a reflection of available moisture): $MD_{aer} = PET_{aer} - ET_{aer}$, and $MD_{noaer} = PET_{noaer} - ET_{noaer}$; PET [mm/day] is calculated using the Hargreaves equation (Hargreaves and Samani, 1985): $PET = 0.0135 \times (Rs*86400/LH_{vap}) \times (T+17.8)$, where Rs is here defined as net shortwave in W/m^2, $LH_{vap} = 2.45\times10^6$ J/kg, T is skin temperature in °C, ET is calculated by converting latent heat [W/m^2] to mm/day. Figure 2 shows FVI in the Sierra Nevada, Rocky, and Cascade Mountains for select months/years (the years with some of the largest LAA in snow were chosen). Positive FVI indicates a greater moisture deficit in the AER case. These regions generally coincide with areas where changes in total soil moisture content were negative (not shown). The most evident impact from springtime changes in SWE, runoff, and consequently summer TSMC occur in California's Sierra Nevada Mountains (Figure 2). This is a region that, as mentioned earlier, does not receive summertime rainfall, and therefore the decrease in SWE and shift in runoff leads to a decrease in summer TSMC. On the other hand, in the southern Rockies, FVI spatial pattern is a mix of positive and negative, with positive FVI values at relatively lower (but still alpine) elevations. This mixed signal could also be a reflection of the influence of summer monsoonal rains on soil moisture storage in this region, which likely hides the impact of a decreased snowpack and reduced runoff on the water budget. In the Cascade Mountains of the Pacific Northwest, where BC is likely the dominant LAA in snow, the LAA in snow-induced changes in SEB and WB are relatively smaller, and as such, the impact on soil moisture and fire risk is less obvious, or perhaps less intense. Additionally, because of the synoptics of the region, seasonal rains likely compensate a decrease in summertime TSMC due to LAA in snow.

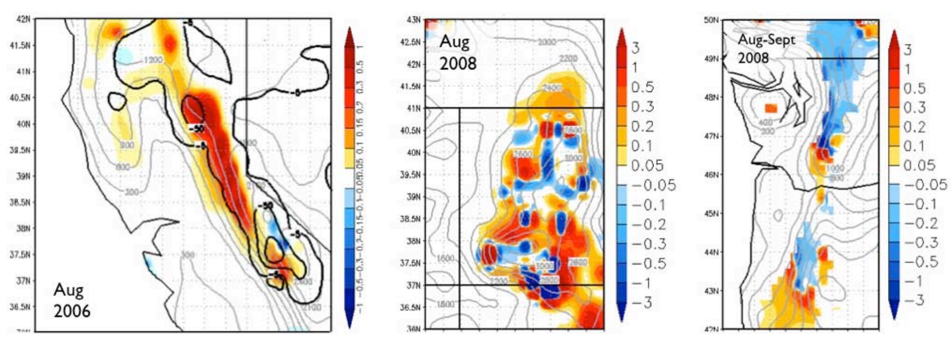

Figure 2. Fire vulnerability index for Sierra Nevada, Rocky, and Cascade Mountains, respectively, for select months.

SUMMARY AND CONCLUSIONS

While LAA in snow have a clear impact on the energy and water budgets of WUS, causing significant reductions in SWE, shifting runoff to earlier, and in some cases decreasing total runoff, the implications of these effects to wildfire risk is less straightforward. In mountain regions that are already soil moisture limited, and which are prone to wildfires, such as the Sierra Nevada in CA, our modeling study suggests LAA in snow could exacerbate these conditions, increasing the risk to wildfires by further drying the soils due to earlier and reduced snowmelt, in particular at higher elevations, above 1500-2000 m. Regions like the Pacific Northwest and southern Rocky Mountains, which receive storm track or monsoonal precipitation in the spring and/or summer months, do not exhibit clear implications to increased wildfire risk from the seasonal impact of LAA in snow, despite seeing significant reductions to the snowpack and changes in runoff (the southern Rockies in particular). Further research is needed to disentangle the potential ramifications of LAA-in-snow–reduced snowpack/runoff to wildfire risk in mountain regions.

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