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Discussion

# Comments on “Impact of California’s Air Pollution Laws on Black Carbon and their Implications for Direct Radiative Forcing” by R. Bahadur et al.

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ABSTRACT

Using data from the Interagency Monitoring of Protected Visual Environments (IMPROVE) program, Bahadur et al. (2011) report that average fine particulate light absorbing carbon (LAC) concentrations in California decreased by about 50% from 0.46 μg m$^{-3}$ in 1989 to 0.24 μg m$^{-3}$ in 2008. They attribute most of the LAC decline in California to reductions in the state’s diesel emissions. These findings are encouraging, but in this comment we call attention to a significant methodological issue that can arise in any long-term trends analysis using IMPROVE data. In the Bahadur et al. analysis, LAC data from eighteen remote monitoring sites were aggregated with data from three urban sites that only operated for 1–8 years. The large absolute decrease of 0.22 μg m$^{-3}$ they reported in the statewide California average was largely driven by one urban site, South Lake Tahoe (Tahoe), which was dropped from the network in mid-1997. LAC concentrations at Tahoe were an order of magnitude higher than those at nearby Bliss State Park indicative of large local source contributions. The exclusion of the three locally influenced urban sites substantially reduces the magnitude of the decreasing LAC trends shown in Bahadur et al., though this does not necessarily invalidate the paper’s conclusion that LAC is broadly decreasing and diesel emission controls are likely to be responsible for part of this decrease. Control of emissions from wood-burning stoves may also have contributed to decreases in LAC and other particulate compounds; like diesel emission controls, this too is an important regulatory success.



## 1. Introduction

The Interagency Monitoring of Protected Visual Environments (IMPROVE) program collects 24-h filter samples of fine (<2.5 μm) and total (<10 μm) particulate matter every third day (Malm et al., 1994). The fine particulate ($PM_{2.5}$) samples are analyzed for elemental, ionic, and carbonaceous content, including light absorbing carbon (LAC) determined with a thermal optical reflectance (TOR) method. Since its 1988 debut, the IMPROVE monitoring network has been operated in a manner designed to promote consistent measurements; necessary changes are preceded by extensive testing of equivalency to minimize discontinuities in the time series. Since promulgating the Regional Haze Rule (RHR) in 1999, the Environmental Protection Agency has relied on IMPROVE data to track long-term temporal changes in haze and its particulate constituents in protected visual environments (U.S. EPA, 1999).

A number of studies have examined trends in IMPROVE data (e.g., Sister and Malm, 2000; Malm et al., 2002; Brewer and Adlhoch, 2005; Jaffe et al., 2005; White et al., 2005; Murphy et al., 2011). In their recent addition to this literature, Bahadur et al. (2011) used IMPROVE LAC as a surrogate for black carbon (BC) and report that “Annual average BC concentrations in California have decreased by about 50% from 0.46 μg m$^{-3}$ in 1989 to 0.24 μg m$^{-3}$ in 2008”. Black carbon is of interest for its role as an efficient short-lived, positive radiative forcer (Jacobson, 2005) and its potential contribution to adverse health effects (U.S. EPA, 2009). Bahadur et al. attribute most of the LAC decline in California to reductions in the state’s diesel emissions, which also decreased approximately 50% from 1990 to 2008. Their findings are encouraging and welcome, but we call attention to a significant methodological issue that can arise in any contemplation of long-term trends in IMPROVE data.

The national IMPROVE network currently consists of about 170 monitoring sites, the majority of them added since 1999, to support the requirements of the RHR. Most of these are located in remote settings where their sampling of anthropogenic materials can be assumed to be representative of broad surrounding areas, but a small number are located in urban settings and are highly influenced by local sources of emissions. Fig. 1 illustrates these distinctions for

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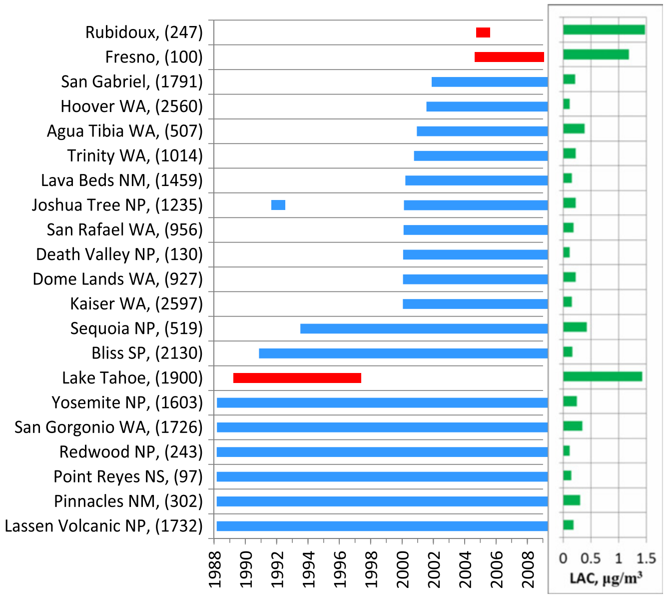


**Fig. 1.** The twenty-one IMPROVE monitoring sites in California, their periods of operation, and their grand-average EC concentrations. Area designations (NM, National Monument; NP, National Park; NS, National Seashore; SP, State Park; WA, Wilderness Area) and elevations in m above sea level are listed after site names. Remote sites are in blue and urban sites are in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the California sites used by Bahadur et al. While some California sites have operated continuously through the authors' period of analysis, the reported LAC trend is for the annual mean of valid data from all sites operating in a given year and thus rests on different sites in different years. Such aggregation can be justified if each year's sites are in some sense drawn at random from a common distribution of site characteristics, but this interpretation appears untenable in the case at hand. Our discussion is intended as a methodological caveat relevant to any long-term trends analysis using IMPROVE data and is not meant to dispute or endorse the Bahadur et al. conclusions.

## 2. Trends in California data coverage

As shown in Fig. 1, there were twenty-one locations in California with IMPROVE particulate monitors that operated between 1988 and 2008. Eighteen of these sites are located in or represent protected natural areas; their remote settings span California from the south to the north and from the coast to the high Sierra Nevada mountains and Mojave Desert, ranging in elevation from near sea level to 2600 m. Eight of these remote sites began operating between 1988 and 1994, but the other ten began operation only after 2000. Three other IMPROVE sites are located in urban settings. One monitor operated briefly in Rubidoux, an unincorporated exurb of Los Angeles with a population of over 30,000, a second in Fresno, a city of over half a million people located in the center of the San Joaquin Valley, and the third in South Lake Tahoe, hereafter referred to as Tahoe, a recreation-oriented city with a population of over 20,000 in the Sierra Nevada mountains. None of these urban sites sampled for the entire 20-year period, with Tahoe being retired in summer 1997 and Fresno and Rubidoux beginning operation in fall 2004.

The average LAC concentration over each site's time series is presented in Fig. 1. Although the eighteen remote IMPROVE sites are in diverse settings, average LAC concentrations at these sites are all 0.4 μg $m^{-3}$ or less. In contrast, the three locally influenced sites all show average LAC concentrations of 1.2 μg $m^{-3}$ or more. Fig. 2

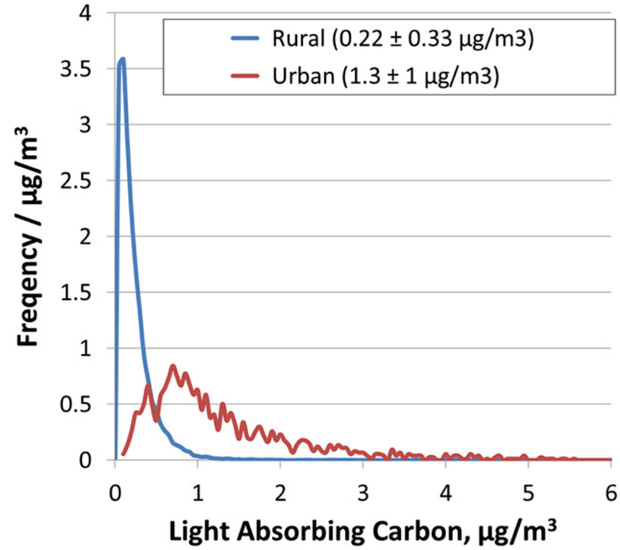


**Fig. 2.** Frequency distributions of daily LAC at 18 remote and 3 urban sites. Also shown in the legend are the mean and standard deviation of each distribution.

shows a relatively narrow range of variation for daily LAC concentrations at remote sites, suggesting that adding or removing such monitors may not greatly influence trends in the statewide average. It is evident from the much higher concentrations and broader distribution for the urban sites that their entry to or exit from the network has a much greater impact on the calculation.

Fig. 3 illustrates the sensitivity of the California LAC trend to three different groups of sites used in its calculation. The highlighted series shows the LAC concentrations from all available urban and rural sites averaged together and is similar to that presented by Bahadur et al. As they noted, there is a steep decreasing trend from 1992 to 1998 and then the LAC time series flattens out. The overall trend spans three successive measurement intervals, each influenced by a different mix of remote and urban sites. The 1989–1997 LAC averages pooled data from six to nine remote sites with locally influenced measurements from Tahoe. The 1998–2003 averages used data only from remote sites. The 2004–2008

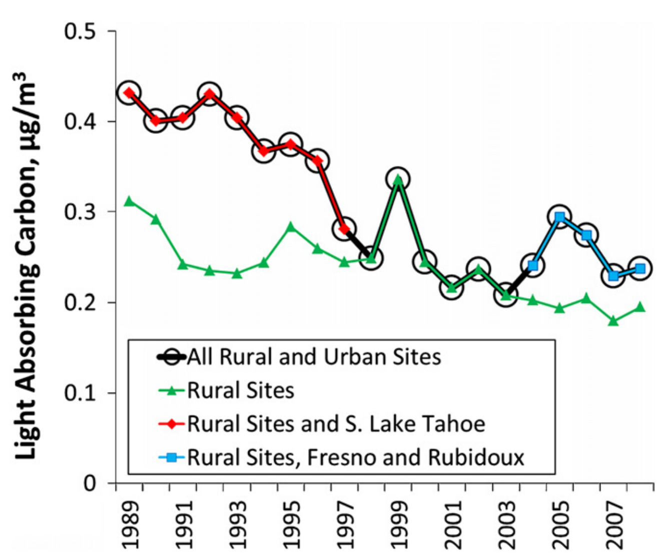


**Fig. 3.** Long-term trends in California LAC averaged over different urban and rural combinations of monitoring sites.

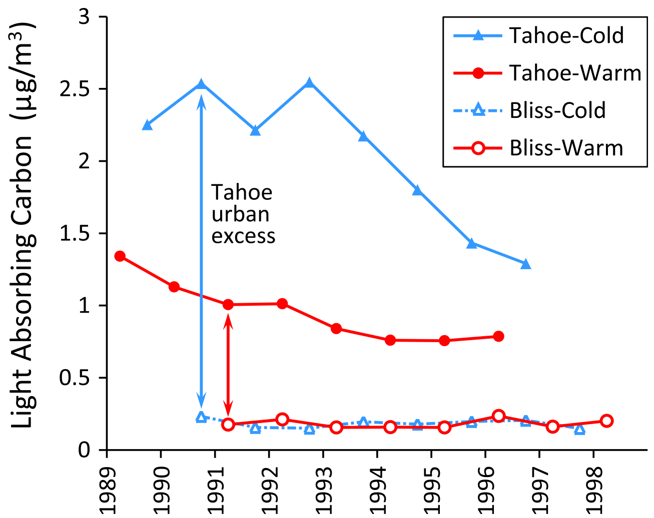


**Fig. 4.** Long-term LAC trends at South Lake Tahoe and Bliss for a cold (October–March) and a warm (April–September) season. South Lake Tahoe data are not shown for 1997 because monitoring there ended June 1997, in midseason.

averages pooled data from eighteen remote sites with measurements in urban Fresno and Rubidoux.

Excluding urban measurements from the aggregation produces significantly different trends. As shown in Fig. 3, the large decrease from 1992 to 1998 is no longer present. Also, the LAC concentrations now have a decreasing trend from 2000 to 2008. The average LAC trend (not shown) for the six rural sites operating throughout the program tracks the rural LAC trend shown in Fig. 3 for all rural sites operating in a given year, indicating that the rural data are from a homogeneous distribution and suitable for integrated trend analysis.

## 3. The Localized extent of LAC at South Lake Tahoe

Fig. 3 demonstrates that the large contribution of the Tahoe measurements to average California LAC concentrations in the 1990s drives the large apparent decrease in LAC. The location of the Tahoe monitor, in the city and near the lake shoreline, served as a site for studies of winter haze episodes since before the IMPROVE program (Pitchford and Allison, 1984). The overnight-peaking haze was thought to be dominated by wood smoke, and residential wood smoke regulations were established to reduce these emissions. In 1990, emissions from wood heaters were restricted. In January 1993, a wood heater retrofit program (Tahoe Regional Planning Agency, 1999) was established in which all of a building's wood heaters had to meet the new emission standards prior to its sale. Fig. 4 shows that cold-season LAC concentrations at Tahoe were flat from 1989 to 1993 at ~2.4 µg $m^{-3}$ and then rapidly decreased to ~1.3 µg $m^{-3}$ in 1996. The warm season concentrations were lower and showed less downward trend, with LAC decreasing between 1992 and 1996 by about 50% and 25% in the cold and warm seasons, respectively.

It is notable that the IMPROVE site at D.L. Bliss State Park, also in the Lake Tahoe basin just 7 miles to the northwest and 230 m higher in elevation than Tahoe, recorded a quite different picture of the 1990s. Fig. 4 shows that LAC concentrations at Bliss were about ~0.18 µg $m^{-3}$ in both seasons, with little or no trend between 1989 and 1996. The order-of-magnitude difference between concentrations at Tahoe and Bliss places strong limits on the horizontal and vertical extent of the Tahoe LAC as well as contributions from regional and distant sources to the Tahoe basin.

The high cold-season concentrations recorded at Tahoe appear to result from surface inversions that restrict local emissions from wood heaters and other sources to a shallow layer, a conclusion consistent with the strong nocturnal peaks shown by Pitchford and Allison (1984) for light scattering data. The depth of the LAC layer is obviously a critical factor in estimates of radiative forcing from near-surface concentration data.

## 4. Discussion

California state LAC concentration trends are most appropriately based on regional (remote or rural) or long-term IMPROVE monitoring sites. The exclusion of three locally-influenced sites operated in population centers for limited periods substantially reduces the magnitude of the decreasing LAC trends shown in Bahadur et al., though it does not necessarily invalidate the paper's conclusion that LAC is broadly decreasing and diesel emission controls are likely to be responsible for part of this decrease. Control of emissions from wood-burning stoves may also have contributed to decreases in LAC and other particulate compounds; like diesel emission controls, this too is an important regulatory success.

## Disclaimer

The assumptions, findings, conclusions, judgments, and views presented herein are those of the authors and do not represent those of the National Park Service (NPS), National Oceanic and Atmospheric Administration (NOAA), and University of California.

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