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Discussion

Response to 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

We address possible sampling biases reported in an earlier work (Bahadur et al., 2011) relating decreases in black carbon (BC) measurements from the IMPROVE monitoring network to diesel emissions in California. A decrease in average BC concentration of between 40 and 60% is found at each site between 1988 and 2007, consistent with the statewide average of 50%. No significant regional biases are found to drive these trends, which are independent of latitude as well as mean BC concentration. We find no reason to revise the conclusions of Bahadur et al, in response to the methodological issues raised by Schichtel et al.
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1. Introduction

In a recent publication (Bahadur et al., 2011) we reported trends in atmospheric BC based on data from the IMPROVE network. We also report a possibly causative relationship between an observed decrease in both Diesel BC emissions (from 0.013 Tg Yr^{-1} in 1990 to 0.006 Tg Yr^{-1} by 2008) and measured BC (0.46 μg m^{-3} in 1989 to 0.24 μ gm^{-3} in 2008) over California. In their comment, Schichtel et al. call attention to methodological issues that may have biased our analysis, specifically – a bias introduced by the spatial and temporal inhomogeneity of the sampling sites and the higher concentrations in urban sites biasing the average trends. To support their contention they take the specific case of the urban site in South Lake Tahoe, where BC reductions could be dominated by reductions in residential wood burning. Here, we provide additional analyses to address these concerns, and conclude that the methodological issues raised by Schichtel et al are either not valid or do not alter our findings.

2. Potential biases from inhomogeneous data coverage

Although the IMPROVE network has been in continuous operation since 1987, Schichtel et al. correctly point out that its coverage has not been temporally uniform. In order to raise their methodological concerns, they focus solely on Bahadur et al's Fig. 1, which shows averages over all of the sites. Had we relied solely on Fig. 1 to arrive at our conclusions, the methodological issue they raise would be relevant. As Fig. 2 of our paper shows, the annualized trends at individual stations are consistent with the trend from the averages of BC over all stations. Perhaps this point was not made explicit in our paper. The following analyses and discussion addresses the methodological issue raised by Schictel et al. more explicitly.

Any significant biasing of the statewide trend can be understood by examining the non-aggregated trends at the 6 sites with complete coverage between 1988 and 2007. These sites are illustrated in Fig. 1(a) and span the entire geographic extent of California, providing a reasonable sampling cross-section. Fig. 1(b) illustrates the trends in annual means for measured BC at each of these stations. Similar to the statewide trend, we see a high interannual variability, which still gives rise to a total decrease at the decadal time scale. In fact, the decrease between 1988 and 2007 at each of the sites is found to be comparable to the 50% statewide decrease we reported in our paper, for example 0.22–0.13 μg m^{-3} (−40%) at LAVO, 0.14–0.07 μg m^{-3} (−50%) at PORE, and 0.45–0.20 μg m^{-3} (−55%) at PINN.

Since these 6 sites establish a reliable baseline and confirm Bahadur et al's over all statewide trend from their Fig. 1, we expand our analysis to include all sites with measurements spanning at least 75% of three time periods between 1988–1997, 1998–2007, and 1988–2007. With the exception of South Lake Tahoe (SOLA) these sites are all located in remote areas. To contrast these measurements to urban trends, we also include results from BC measurements collected at three locations in the Bay Area (Kirchstetter et al., 2008; Novakov et al., 2008). Fig. 1(c) shows the

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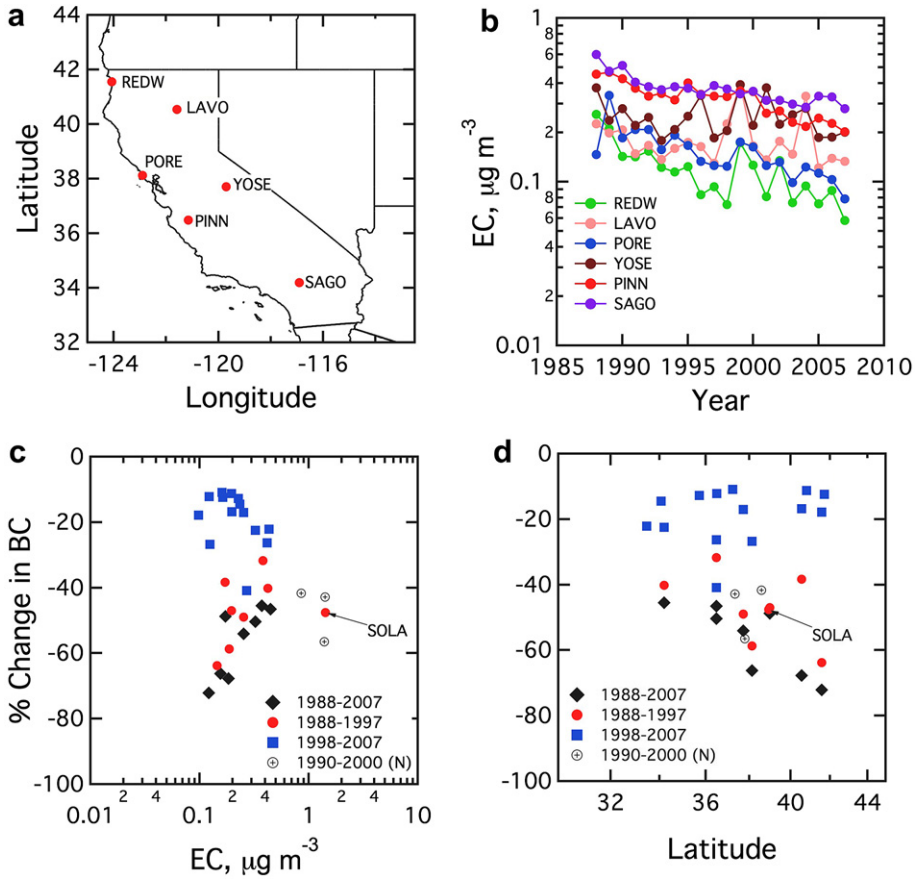

Fig. 1. (a) Location of IMPROVE sampling stations in continuous operation from 1988–2007 in California, (b) Annual means of measured BC at each site in continuous operation (c,d) Average annual rate of change in mean BC concentration for IMPROVE sites with greater than 75% coverage in each time period. Urban measurements from South Lake Takoe (SOLA, labelled) and the Bay Area (designated N) (Novakov et al., 2008) included for comparison.

change in BC as a function of average BC concentrations and Fig. 1(d) shows the change as a function of latitude. At each of these sites we find an average annual decrease between 40 and 70% from 1988–1997 and between 15 and 40% from 1998–2007, which correspond to a total decrease between 40 and 60% at each of these sites matching up well with the statewide average of 50%. We do not find any correlation with either the total BC concentration or latitude, indicating that the downward trend is fairly uniform across the state, in both rural and urban areas and is unlikely to be biased by a few outliers.

3. The role of urban sites in trend analyses

The next major methodological issue raised by Schichtel et al. concerns the inclusion of urban sites in trend analyses. Such a concern would be legitimate had Bahadur et al focused on long-lived greenhouse gas trends, but Bahadur et al's focus was on BC trends for which urban locations are just as important as rural locations in obtaining average trends. Rather, Bahadur et al's analyses would have been more representative had there been more IMPROVE locations in urban sites. This is a rather moot issue, since the trends we see in individual stations are not strongly dependent on either the absolute concentrations or on the geographical location (see Fig. 1 above). In fact, the trends in urban stations are similar to those in rural sites. There is one major misunderstanding by Schichtel et al which may help clarify the situation. They focus excessively on the representativeness of the values for the averages. Of course, we need significantly more stations (of the order of hundreds) to get true representative average BC concentrations for California. But this was neither the focus nor the point in Bahadur et al's analyses – the focus was on trends and Fig. 1 in this paper clearly reveals no biases in the average trend of about 50% reported in Bahadur et al.

4. BC Mitigation at South Lake Tahoe

Regarding the Lake Tahoe urban site, Schichtel et al, make the mistaken assumption that trends in one station can be interpreted solely from local emission sources. In fact, long range transport of pollutants has been well established in the literature (Hadley et al., 2007; VanCuren et al., 2005; VanCuren and Cahill, 2006). Schichtel et al. attribute the decrease in observed BC at the South Lake Tahoe site to mitigation of residential wood smoke emissions following the retrofit program of 1993. The sharp decrease in both organic carbon (OC) and BC starting in 1993 illustrated in Fig. 2(a) is consistent with this conclusion, but may not provide a complete picture. Aerosol phase potassium and a lower EC/OC ratio (compared to fossil fuel emissions) are widely accepted tracers of wood smoke and biomass burning aerosols (Cachier et al., 1989; Echalar et al., 1995; Novakov et al., 2000). If BC reduction were to be attributed solely to wood smoke, we also then also expect to see an increase in the EC/OC ratio and a decrease in the K/EC ratio. Fig. 2(b) reveals, however, just the opposite. It shows that EC/OC ratio decreased while the K/EC ratio increased over the same time period in South Lake Tahoe, contradicting this assertion made by Schichtel et al. The observed trends then raise the interesting possibility that though the total BC emissions attributable to residential wood burning have decreased, the contribution to BC from

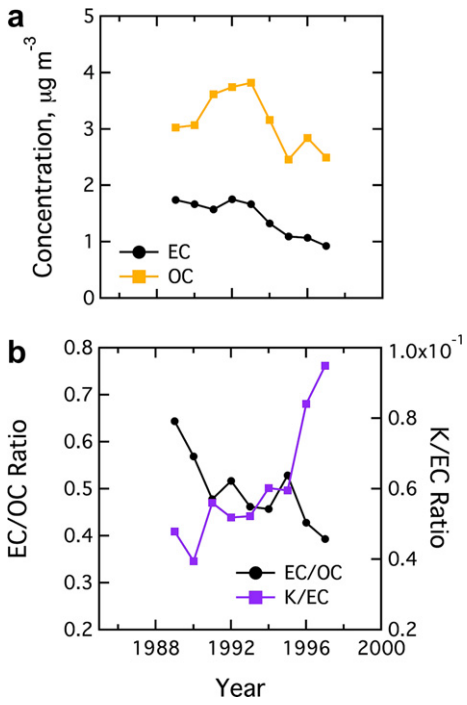

Fig. 2. Annual mean measurements from the South Lake Tahoe (SOLA) station in California for (a) OC and EC absolute concentrations and (b) EC/OC and K/EC ratios.

diesel sources may have decreased at a faster rate. This indicates that even at the South Lake Tahoe site, BC mitigation from diesel sources is a significant factor.

5. Conclusions

Aerosol phase measurements of BC from the IMPROVE monitoring network are found to have decreased between 40 and 60% at each site, consistent with the statewide average of 50% reported in our earlier work (Bahadur et al., 2011). No significant regional biases are found in these trends. In addition to regional efforts (such as at Lake Tahoe), the regulation of diesel fuel emissions in California is a major driving force in BC mitigation.

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