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Widespread reductions in haze across the United States from the early 1990s through 2011

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HIGHLIGHTS

- Trends in the reconstructed mean 20% haziest extinction were computed.
- Trends were computed at remote sites across the United States since 1990s.
- Simulated images of national parks show dramatic improvement in visibility.

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ABSTRACT

Visibility has improved significantly at many remote areas across the United States since the early 1990s. Trends in visibility were calculated using ambient light extinction coefficients (b_{ext}) estimated from speciated particulate concentrations measured by the IMPROVE (Interagency Monitoring of Protected Visual Environments) network. The 20% haziest b_{ext} levels were computed for each year following Regional Haze Rule guidelines and aggregated over three major regions of the United States. Over the last two decades (1992–2011) the regional mean 20% haziest b_{ext} dropped by 52% ($-2.6\%\ yr^{-1}$, $p < 0.01$) in the eastern United States, and by 20% ($-1.0\%\ yr^{-1}$, $p = 0.08$) for sites along the West Coast. However, in the Intermountain/Southwest region, the trend was insignificant ($-0.2\%\ yr^{-1}$, $p = 0.36$). Over the last decade (2002–2011) the haziest b_{ext} in the Intermountain/Southwest region decreased by 15% ($-1.5\%\ yr^{-1}$, $p = 0.09$), compared to a decrease of 35% ($-3.5\%\ yr^{-1}$, $p = 0.06$) in the West Coast region and 50% ($-5.0\%\ yr^{-1}$, $p = 0.02$) in the East. A novel aspect to this study is the visualization of trends through the simulation of images of national parks and other remote areas for early and current haziest conditions. These images are an effective means for communicating trends and illustrate the dramatic improvement in visibility, especially in the East, where reductions in sulfate concentrations and sulfur dioxide emissions have had a positive impact on visibility degradation. However, while conditions are clearer for regions in the West, less improvement points to the need for understanding the influences on the trends in haziest conditions in those regions.

1. Introduction

Visibility has long been considered an important aspect of air quality protection in national parks and the United States. For example, the stated purpose of the National Park Service Organic Act of 1916 was "… to conserve the scenery and the natural and historic objects and the wildlife therein and to provide for the enjoyment of the same in such a manner and by such means as will leave them unimpaired for the enjoyment of future generations" (U.S. Code 16.1.1). With the passing of the Clean Air Act (CAA) (U.S. Code 42.85) in 1970 and the formation of the Environmental Protection Agency (EPA), major regulatory programs were developed that included national ambient air quality standards (NAAQS). The CAA amendments of 1977 introduced additional protection for

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certain national treasures. One stated purpose of Part C of the amendments, Prevention of Significant Deterioration of Air Quality, was "to preserve, protect, and enhance the air quality in national parks, national wilderness areas, national monuments, national seashores, and other areas of special national or regional natural, recreational, scenic, or historical value" (U.S. Code 42.7470). These special areas were designated as class I areas (CIA) and included international parks, national wilderness areas, and national memorial parks that exceeded 5000 acres in size and national parks that exceeded 6000 acres in size in existence on the date of enactment of the 1977 CAA amendments (U.S. Code 42.7472). Section 169A of the 1977 CAA amendments declared as a national goal "… the prevention of any future, and the remedying of any existing, impairment of visibility in mandatory class I federal areas which impairment results from manmade air pollution" (U.S. Code 42.7491). Section 169B of the 1990 CAA amendments focused attention on regional haze and was specifically designed to address visibility issues by expanding visibility monitoring networks and requiring studies to investigate the formation and transport of haze (U.S. Code 42.7492). Other provisions of the 1990 amendments that were designed to reduce the impacts of air pollution on health also affect visibility. Title I addressed the designation of NAAQS nonattainment areas as well as interstate and intercontinental transport, and Title II addressed motor vehicle emissions and fuel standards. Title IV (Acid Deposition Control) established regulatory mandates to reduce electric utility emissions of sulfur dioxide (SO_2) and nitrogen dioxides (NO_x), both of which form particulates in the atmosphere that contribute to visibility degradation and to acid deposition (U.S. Code 42.7651).

The recognition of and response to interstate pollution issues led to the promulgation of the Regional Haze Rule (RHR) by the EPA in 1999 (U.S. EPA, 1999). The RHR was established to achieve the national visibility goal established by Section 169A and called for the elimination of anthropogenic visibility impairment in 156 CIAs by a target date of 2064. Specifically, the RHR calls for no increased impairment of the 20% cleanest conditions and for reasonable progress toward RHR-defined natural visibility conditions for the 20% haziest conditions. Light extinction coefficients (b_{ext}) incorporated by the RHR are reconstructed using an algorithm that accounts for the atmospheric attenuation of visible solar radiation due to scattering and absorption by major aerosol species and by molecular scattering (Rayleigh) using measurements of speciated aerosol concentrations from the Interagency Monitoring of Protected Visual Environments (IMPROVE) network (Malm et al., 1994a; Pitchford et al., 2007). The haze index in deciview units (dv), a logarithmic transformation of reconstructed b_{ext} (Pitchford and Malm, 1994), was selected to track haze levels for the RHR. Five-year periodic assessments are required from each state to evaluate its progress toward achieving natural visibility conditions by 2064 as defined by the RHR. A review of progress toward these goals for the baseline period (2000–2004) and for period 1 (2005–2009) was reported in chapter 9 of Hand et al. (2011).

Developing successful mitigation strategies to achieve regulatory goals such as the RHR requires an understanding of the major aerosol species that contribute to visibility degradation. These contributions vary both seasonally and spatially, as described in Hand et al. (2011) for 2005–2008 monthly mean reconstructed b_{ext} at the surface. In the eastern United States, extinction due to ammonium sulfate contributed 60–70% to visibility degradation on an annual basis and even higher during summer (Brewer and Adlhoch, 2005; Brewer and Moore, 2009), due to high industrial SO_2 emissions and sulfate concentrations in the region (Hand et al., 2012a). Contributions from ammonium sulfate to b_{ext} were much lower in the West (10–30%). Monthly mean contributions to reconstructed b_{ext} at the surface from particulate organic matter (POM) in the East ranged from 5% to 20%. Contributions to haze from POM were greatest in the western United States (40–70%), with the highest contributions in northern California, Montana, and Idaho, due to biomass burning and biogenic emissions (e.g., Jaffe et al., 2008; Schichtel et al., 2008; Holden et al., 2011). Major contributions from ammonium nitrate occurred in the central United States and southern California (30–40% annually and up to 50% in winter), with lower contributions in the East and Southwest (~10%). Contributions from elemental carbon (EC) were around 10% in the West and ~5% in the East. Fine soil contributions to b_{ext} were only a few percent in the East and ranged up to 10% or higher in the Southwest. Sea salt contributions were insignificant except at some coastal sites.

Changes in visual air quality over time can be quantified through trend analyses that provide an evaluation of progress toward meeting regulatory goals and gauge success of emission reduction programs. A study by Schichtel et al. (2001) reported human visual range measurements at nearly 300 meteorological stations across the United States that indicated a significant decrease in haziness from 1980 to 1995. Decadal trends in aerosol optical properties from measurements through 2010 at remote stations in the Northern Hemisphere and Antarctica suggested that light scattering by particles at most North American stations had significantly decreased since the early/mid-1990s and 2000s (Collaud Coen et al., 2013). Other studies have investigated trends in haze-causing particulates in remote regions, but not necessarily their effects on visibility or on the visual scene (Malm et al., 2002; Murphy et al., 2011; Hand et al., 2012a, 2013).

Demonstrating the impact of the change in visual air quality over time on a given scene is a powerful method for communicating trends in visibility. To this end, we simulated images of national parks and other remote areas corresponding to early and current haze levels using visualization software (Air Resource Specialists, Fort Collins, CO). Haze levels were computed following RHR guidelines for the 20% haziest reconstructed b_{ext} levels for long-term (1990–2011) and short-term (2000–2011) individual IMPROVE sites, as well as for narrowed time periods for regionally aggregated sites. Changes in IMPROVE annual mean fine particulate mass concentrations and the EPA's National Emission Inventory's total annual gaseous emissions were also evaluated. Combining the analyses of trends in haze and particulate mass concentrations and gaseous emissions with the demonstrable impacts of the changes on a scene is an effective means by which to evaluate trends in visual air quality. This evaluation is useful for assessing the national goals and regulatory programs designed to reduce particulate concentrations and thereby improve visibility at remote areas in the United States.

2. Experimental

The IMPROVE network collects 24-h samples every third day from midnight to midnight local time, and concentrations are reported at ambient conditions. Inorganic anions are analyzed by ion chromatography and are artifact corrected, carbonaceous aerosols (organic, OC, and elemental, EC) are analyzed by thermal optical reflectance (TOR) and are artifact corrected, elemental concentrations are determined by X-ray fluorescence, and $PM_{2.5}$ and PM_{10} mass concentrations are determined through gravimetric weighing. Additional details regarding IMPROVE site location, sampling, analysis methodology, and detailed descriptions of network operations and data analysis have been previously reported (Malm et al., 1994a; Hand et al., 2011, 2012b). IMPROVE data advisories were followed for the data reduction and analysis in this study (http://vista.cira.colostate.edu/improve/Data/QA_QC/Advisory.htm).