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Errors in representing regional acid deposition with spatially sparse monitoring: Case studies of the eastern US using model predictions

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ABSTRACT

The current study uses case studies of model-predicted regional precipitation and wet ion deposition over 5-year periods to estimate errors in corresponding regional values derived from the means of site-specific values within regions of interest located in the eastern US. The mean of model-predicted site-specific values for sites within each region was found generally to overestimate the corresponding model-predicted regional wet ion deposition. On an annual basis across four regions in the eastern US, these overestimates of regional wet ion deposition were typically between 5 and 25% and may be more exaggerated for individual seasons. Corresponding overestimates of regional precipitation were typically <5%, but may be more exaggerated for individual seasons. Period-to-period relative changes determined from the mean of site-based model-predicted wet deposition for the current regional ensembles of sites generally estimated larger beneficial effects of pollutant emissions reductions in comparison to changes based on model-predicted regional wet deposition. On an annual basis site-based relative changes were generally biased low compared to regional relative changes: differences were typically <7%, but they may also be more exaggerated for individual seasons. Spatial heterogeneities of the wet ion deposition fields with respect to the sparse monitoring site locations prevented the monitoring sites considered in the current study from providing regionally representative results. Monitoring site locations considered in the current study over-represent the geographical areas subject to both high emissions and high wet ion deposition and under-represent the geographical areas subject to low emissions and low wet deposition. Since the current case studies consider only those eastern US site locations that have supported concurrent wet and dry deposition monitoring, similar errors may be expected for dry and total deposition using results from the same monitoring site locations. Current case study results illustrate the approximate range of potential errors and suggest caution when inferring regional acid deposition from a network of sparse monitoring sites.

1. Introduction

Chemical species contained in air pollutant emissions are frequently transformed through chemical and physical processes in the atmosphere before they are deposited to the surface of the Earth. Acid deposition occurs when chemical species that can alter the acid–base balance of ecosystems are transferred from the atmosphere to the surface. Acid deposition is also spatially and temporally variable, stressing both landscapes and ecosystems, and can occur by dry deposition of gases and aerosols and by wet deposition from clouds, fogs and precipitation. The effects of acid deposition are diverse, ranging from eutrophication of coastal waters to acidification of lakes, streams, and forest soils with attendant reductions in species diversity (Dennis et al., 2007).

Acid deposition monitoring networks have been established to meet various goals (e.g., determining trends, spatial patterns, and site-specific behaviour). The Clean Air Status and Trends Network (CASTNET) estimates dry deposition using air quality and meteorological data monitored at more than 90 sites (53 east of the Mississippi River) by the US Environmental Protection Agency (US EPA) and the National Park Service (NPS). An archive of these data and estimates of dry deposition is maintained by the US EPA (http://www.epa.gov/castnet/). For the period between 1990 and 2004, several recent studies indicate that the number of dry deposition sites in the eastern US with relatively complete data records range between 30 and 40 (Holland et al., 1999, 2004; Baumgardner et al., 2002; Mueller, 2003; Sickles and Shadwick, 2007a,b). Wet

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deposition is monitored in the United States (US) at more than 250 National Atmospheric Deposition Program/National Trends Network (NADP/NTN) sites (127 east of the Mississippi River). An archive of these and related data is maintained by NADP (http://nadp.sws.uiuc.edu/).

For a given chemical species, the sum of dry deposition and wet deposition of that species is termed total deposition. Although dry and wet deposition monitoring sites are frequently collocated, there is a relatively small number of paired CASTNET dry and NADP wet deposition monitoring sites with a sufficiently complete record to permit long-term examination of observed total deposition at these paired sites. Since the dry deposition network has fewer sites (see above), the number of paired sites available to yield observed total deposition is usually limited by the existing dry deposition monitoring sites.

Deposition of a relevant chemical species (e.g., sulfur or nitrogen), represents the amount of that chemical species deposited to an area, or a region, over a period of time and is often expressed in units of kg ha^{-1} y^{-1}. Acid deposition is frequently considered to be a regional stressor of landscapes and ecosystems, where the region may range in size from a small watershed or forest to a multistate area. Although the dry and wet deposition monitoring results, noted earlier, are site-specific, they are sometimes aggregated across sites in an attempt to represent the regions where the sites are located (e.g., see US EPA, 2009). Large regions often have large heterogeneities in their spatial distribution of land cover (e.g., crops to forests), terrain (e.g., flat to montane), pollutant species (e.g., SO_2, NO_2, and NH_3), pollution sources (e.g., agricultural, mobile, and industrial), and pollutant emissions density. These varied features influence the magnitude and spatial distribution of both dry and wet deposition and may be responsible for sizeable differences reported for nearby monitors (Brook et al., 1997; Reid et al., 2001; Gego et al., 2005). In those cases where quantification of total deposition to a large (e.g., multistate) region is desired, it is tempting to use the mean (or some other measure of central tendency) of the total deposition values monitored within a region of interest as an index of its regional value (e.g., see US EPA, 2009). It is unlikely, given the previously noted sparse coverage provided by available dry deposition monitoring sites, that currently available monitoring results can be used to provide accurate representations of regional total deposition. It is also unclear if observed changes in regional total deposition aggregated from such a sparse network are regionally representative.

The NADP was established approximately a decade prior to CASTNET. Wet deposition monitoring results from NADP provided guidance in the design of CASNET for the monitoring of dry deposition (Holland et al., 1994). At any given location both dry and wet deposition of common species are influenced in similar ways by common sources and meteorological patterns. As a result, site-specific dry deposition may be estimated to be very roughly proportional to collocated wet deposition (Sullivan et al., 2008). While wet deposition generally exceeds dry deposition at sites in the eastern US, the proportion varies depending on species, site location, and season (Sickles and Shadwick, 2007a). Multi-year finely spatially resolved model estimates of dry deposition are currently not available; however, such estimates are available for wet deposition. The goal of this paper is to use case studies of model-predicted regional wet deposition to estimate errors in regional wet deposition and in temporal changes of wet deposition derived from the means of model-estimated values obtained for the specific sites where only total deposition has been monitored in the eastern US. Although strictly applicable only to the interpretation of wet deposition, the results are given to provide a basis for the inferential interpretation of dry and total deposition monitoring results.

2. Approach

2.1. Description

The goal of the current study is to compare 5-year averages of model-predicted (defined in Section 2.3), finely spatially resolved (i.e., nominally 330-m) regional precipitation and wet sulfate (SO_4^{2-}), nitrate (NO_3^-), ammonium (NH_4^+) and hydrogen (H^+) ion deposition for four regions in the eastern US with the corresponding means of values obtained from the same model-predicted precipitation and wet ion deposition gridded surfaces but at specific monitoring site locations. Comparisons of period-average annual values and of period-average seasonal values are made. The term seasonal refers to precipitation and wet ion deposition values associated with climatic seasons (i.e., winter = December + January + February), while the term annual refers to the summation of the corresponding seasonal values. Model-predicted site-based wet deposition is considered at the specific locations where collocated monitoring of both dry and wet deposition (i.e., total) has occurred over the past 15–20 years. The mean of model-predicted site-specific values was adopted in the current study to estimate site-based regional wet deposition for subsequent comparison with regional model predictions of wet deposition. It is unclear how site-based regional wet deposition estimates based on more complex methods (e.g., distance-weighting) would compare to corresponding regional model predictions of wet deposition.

2.2. Monitoring data

Wet, dry and total deposition, derived from monitoring data collected at or near 34 CASTNET sites located in the eastern US, have been recently examined for the 5-year periods, 1990–1994 and 2000–2004 (Sickles and Shadwick, 2007a,b). Between 1990–1994 and 2000–2004, reductions of emissions densities and corresponding atmospheric concentration and deposition of oxidized sulfur and nitrogen species were reported. In these studies the eastern US was divided into four geographical regions, with 10 sites in the northeast, 10 sites in the midwest, 14 sites associated with the south, and 34 sites in the east, represented by the combination of the previous three regions. These regions and site locations (except for a southern site, located in Arkansas) are illustrated on maps of model-predicted annual wet SO_4^{2-} and NO_3^- deposition for 1990–1994 in Fig. 1a and b. For more information about the sites (e.g., terrain type, elevation, latitude, longitude), see Sickles and Shadwick (2007a,b).

2.3. Model-predicted precipitation and wet ion deposition

Model estimates of average annual and seasonal precipitation and wet ion deposition were made for the eastern US for the two 5-year periods, 1990–1994 and 2000–2004. The model employed is a moving neighborhood, weighted least squares regression algorithm that uses precipitation and wet ion concentration measurements along with elevation, slope and topographic aspect input derived from 3-arc-second US Geological Survey Digital Elevation Model (USGS DEM) output (Grimm and Lynch, 2004). Precipitation, measured daily at approximately 4400 National Oceanic and Atmospheric Administration (NOAA) sites in the eastern US, was used for years prior to 2001. Precipitation for subsequent years was derived from NOAA's radar-based Quantitative Precipitation Estimate data set after bias-correction according to NOAA's Global Historical Climatology Network measurements. A modified, three-pass Barnes (1964) objective analysis algorithm was applied to measurements of quarterly volume-weighted wet ion concentrations summarized from weekly precipitation samples collected at