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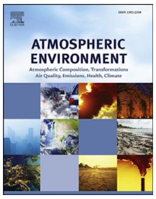

Evaluation of near surface ozone and particulate matter in air quality simulations driven by dynamically downscaled historical meteorological fields

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HIGHLIGHTS

- U.S. decadal air quality simulated using emissions trends and downscaled meteorology.
- Evaluation using observations from AQS, CSN, CASTNet, and IMPROVE monitoring networks.
- Performance comparable to typical retrospective air quality modeling applications.
- Provides confidence in approach for modeling climate change effects on air quality.

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ABSTRACT

In this study, techniques typically used for future air quality projections are applied to a historical 11-year period to assess the performance of the modeling system when the driving meteorological conditions are obtained using dynamical downscaling of coarse-scale fields without correcting toward higher-resolution observations. The Weather Research and Forecasting model and the Community Multiscale Air Quality model are used to simulate regional climate and air quality over the contiguous United States for 2000–2010. The air quality simulations for that historical period are then compared to observations from four national networks. Comparisons are drawn between defined performance metrics and other published modeling results for predicted ozone, fine particulate matter, and speciated fine particulate matter. The results indicate that the historical air quality simulations driven by dynamically downscaled meteorology are typically within defined modeling performance benchmarks and are consistent with results from other published modeling studies using finer-resolution meteorology. This indicates that the regional climate and air quality modeling framework utilized here does not introduce substantial bias, which provides confidence in the method's use for future air quality projections.

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1. Introduction

Air quality is strongly influenced by meteorology, and it is well established that a changing climate will affect future ambient air quality (e.g., Jacob and Winner, 2009; Weaver et al., 2009; Fiore et al., 2015). Many studies that have examined the effects of climate change on air quality have concluded that surface ozone (O_3) levels will likely increase in localized areas due to the projected changes in meteorological conditions (Leung and Gustafson, 2005; Nolte et al., 2008; Katragkou et al., 2011; Kelly et al., 2012; Trail et al., 2014; Fann et al., 2015). This has potential implications for air quality management plans, because the "climate penalty" (Wu et al., 2008) may offset some of the improvements in ambient air quality that would otherwise occur as emissions controls are implemented (Fann et al., 2016), with adverse consequences for human health. One other potential effect of climate change on air quality is a regionally dependent lengthening of the ozone season, historically classified as May through September in most of the United States (e.g., Fiore et al., 2002; Nolte et al., 2008; Weaver et al., 2009; Cooper et al., 2014; Clifton et al., 2014). Accordingly, it is critical to develop a regional modeling framework that can credibly project air quality changes resulting from future climate scenarios.

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For most historical ("retrospective") regional air quality studies using Eulerian models, meteorological conditions are obtained from a comparably scaled meteorological model. Furthermore, the meteorology developed for those retrospective air quality modeling applications assimilates observations where available to achieve the best possible representation of the three-dimensional evolution of the meteorological conditions over the time period of interest (Otte, 2008a,b). Several "dynamic evaluation" air quality modeling studies have been conducted in which the focus is not the air quality model's predictions in comparison to observations, but rather on the model's response to changing emissions or meteorology (e.g., Gilliland et al., 2008; Foley et al., 2015). Hogrefe et al. (2011) conducted an 18-year simulation over the Northeast United States, examining the model's ability to capture the interannual variability in O_3 levels due to meteorology as well as trends due to changes in emissions. In all of these studies, the meteorology was developed by assimilating high-resolution observational data.

When starting from a coarse-scale global modeling framework to simulate regional-scale air quality, dynamical downscaling can be used (Giorgi and Meleux, 2007). In dynamical downscaling, the coarse global data provide input to the regional model through the lateral boundaries and sometimes within the interior domain through "nudging". Interior nudging maintains consistency in the weather patterns between the global and regional models and can reduce errors in the regional model (von Storch et al., 2000; Miguez-Macho et al., 2004; Bowden et al., 2012). Unlike traditional retrospective meteorological modeling, no fine-scale observations are assimilated when downscaling. It is challenging, however, to evaluate the effects of using meteorology downscaled from a global climate model (GCM) for simulating air quality. Fields from a GCM are representative of the climate during that era, e.g., "climate circa 2000," but cannot accurately simulate the weather of the day. It is therefore necessary to model several years to account for interannual variability of meteorological conditions. Also, air pollutant emissions have been changing dramatically over the past few decades, and it is necessary to consider these changes when comparing to measurements taken over multiple years.

In order to evaluate the validity of using downscaled fields to drive future air quality projections, it is important to test the downscaling method using historical coarse-scale global fields without correcting toward higher-resolution meteorological observations. The downscaled meteorology may then be used to drive a chemical transport model, and the results can be compared to historical observations of air quality to ascertain whether future air quality projections based on downscaled meteorology can provide credible results. Only a few studies have been conducted using dynamically downscaled historical meteorology to simulate regional air quality, all of which were focused on Europe (Katragkou et al., 2010; Zanis et al., 2011; Lacressonnière et al., 2012; Menut et al., 2013). Meteorological variables important for simulating air quality, including temperature, precipitation, boundary layer height, and wind speeds, can be degraded when the regional model is driven by dynamically downscaled meteorology (Katragkou et al., 2010; Lacressonnière et al., 2012; Menut et al., 2013). Katragkou et al. (2010) and Zanis et al. (2011) used meteorology downscaled from both the ECMWF ERA40 reanalysis and from the ECHAM5 global climate model to simulate European ozone concentrations over the decade 1991–2000. Katragkou et al. (2010) found that the modeling system adequately reproduced average decadal surface ozone levels at rural monitoring sites, while Zanis et al. (2011) reported that the performance of their modeling system using downscaled meteorology was comparable to that obtained in previous evaluation experiments. Lacressonnière et al. (2012) used both operational meteorological analyses and global climate model data to simulate European air quality, and found that the air quality model driven by climate model data was less skillful in reproducing air pollutant concentrations. However, the differences in model performance indicators between the two frameworks were not substantial, and they concluded that predictions driven by the climate model were adequate to simulate future European pollutant levels and associated health impacts. These studies generally did not consider changing emissions either within the modeling domain or the resulting influence on lateral boundary conditions. As a model sensitivity experiment, Katragkou et al. (2010) found that differences due to plausible changes in chemical boundary conditions were comparable to biases attributable to using meteorology from ECHAM5 rather than ERA40.

In this study, we conduct an 11-year simulation of air quality in the United States and evaluate model performance driven by downscaled historical meteorological fields that are not enhanced with high-resolution meteorological observations. The downscaled meteorology used here is meant to emulate the coarseness (in space and time) of a future climate scenario provided by a GCM. Year-specific emission estimates are used to capture the large changes in various precursor emissions that occurred in the United States over the modeled years both within the United States (Xing et al., 2013) and globally (European Commission, 2011). The resulting air quality fields for the historical period are compared against observations from four national networks. Biases in ozone (O_3), total fine particulate matter ($PM_{2.5}$), and speciated fine particulate matter, including sulfate (SO_4^{2-}), ammonium (NH_4^+), nitrate (NO_3^-), and organic carbon (OC), are compared to results typically attained in retrospective air quality model simulations forced by high-resolution, observation-driven dynamic analyses of the meteorological conditions. To our knowledge this work is the longest and most comprehensive air quality modeling study conducted to date using downscaled historical meteorology over the continental United States.

2. Modeling configuration

The meteorology used for this study was generated by the Weather Research and Forecasting (WRF) model (Skamarock and Klemp, 2008) version 3.4.1. North America was modeled using a two-way nested 108-36-km configuration and 34 vertical layers up to 50 hPa. WRF was driven by 2.5° × 2.5° reanalyses from the National Centers for Environmental Prediction-Department of Energy Atmospheric Model Intercomparison Project ("R2") (Kanamitsu et al., 2002). WRF was initialized 00 UTC 2 December 1987 and run continuously through the end of 2010. The physics options in WRF followed Otte et al. (2012), except the present study used the Kain-Fritsch subgrid cloud parameterization with radiative feedbacks (Herwehe et al., 2014). The U.S. Geological Survey (USGS) 24-category land use classification was used. The Meteorology-Chemistry Interface Processor (Otte and Pleim, 2010) v4.2 was used to prepare WRF outputs for CMAQ.

In WRF, two variants of nudging are available for gridded fields: analysis nudging (or grid nudging) and spectral nudging. Analysis nudging is typically used for retrospective air quality modeling applications with WRF (Otte, 2008a,b), and it is appropriate because observations can be incorporated into the fields that are nudged so that they represent the spatial scales well. Spectral nudging (von Storch et al., 2000; Miguez-Macho et al., 2004) is often preferred by the regional climate modeling community because observations are not available in future climate scenarios and spectral nudging can be used to preserve the characteristics of the large-scale flow. See, for example, comparisons of analysis nudging and spectral nudging within WRF by Liu et al. (2012), Bowden et al. (2012, 2013), Otte et al. (2012), and Omrani et al. (2013). In this study we employed spectral nudging at all levels