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Does temperature nudging overwhelm aerosol radiative effects in regional integrated climate models?

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HIGHLIGHTS

- Temperature changes due to nudging are converted to pseudo radiative effects (PRE).
- The domain mean PRE is smaller than aerosol effects at surface and in atmosphere.
- Nudging could be applied to the integrated models to study ARE at regional scales.
- Integrated models with nudging need be treated with caution to study local scale ARE.

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ABSTRACT

Nudging (data assimilation) is used in many regional integrated meteorology-air quality models to reduce biases in simulated climatology. However, in such modeling systems, temperature changes due to nudging could compete with temperature changes induced by radiatively active and hygroscopic short-lived tracers leading to two interesting dilemmas: when nudging is continuously applied, what are the relative sizes of these two radiative forces at regional and local scales? How do these two forces present in the free atmosphere differ from those present at the surface? This work studies these two issues by converting temperature changes due to nudging into pseudo radiative effects (PRE) at the surface (PRE_sfc), in troposphere (PRE_atm), and at the top of atmosphere (PRE_toa), and comparing PRE with the reported aerosol radiative effects (ARE). Results show that the domain-averaged PRE_sfc is smaller than ARE_sfc estimated in previous studies and this work, but could be significantly larger than ARE_sfc at local scales. PRE_atm is also much smaller than ARE_atm. These results indicate that appropriate nudging methodology could be applied to the integrated models to study aerosol radiative effects at continental/regional scales, but it should be treated with caution for local scale applications.

1. Introduction

Meteorology is an important driver for chemical transport models, popularly known as air quality models. Several studies have documented the importance and impacts of meteorology (e.g., temperature, wind, and humidity) on air quality predictions (Jacob and Winner, 2009; Godowitch et al., 2011). Thus, to generate better meteorological inputs, nudging methodologies have been used to drive off-line air quality models to improve model's capability to simulate and understand chemistry/aerosols at global scales (Jöckel et al., 2006; Tilmes et al., 2015; He et al., 2015) and regional scales (e.g., Binkowski and Roselle, 2003). With the rapid development of computer resources and improved understanding of meteorology-chemistry interactions, several integrated or on-line coupled models (which include impacts of air pollutants on meteorology) have been developed to study feedbacks associated with the

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climate-chemistry-aerosol-cloud-radiation system (e.g., Zhang, 2008). For example, the Weather Research and Forecasting model integrated with a Chemistry model (WRF-Chem, Grell et al., 2005; Fast et al., 2006) and the two-way coupled WRF with the Community Multiscale Air Quality Modeling System (WRF-CMAQ, Wong et al., 2012) were developed to estimate the direct and indirect effects of aerosol on regional scales (Forkel et al., 2012; Yu et al., 2014; Wang et al., 2015).

Due to the complex nature of these coupled models, it is more challenging to accurately simulate meteorology. Currently, there are two commonly utilized approaches applied to the integrated models for a precise simulation of meteorology. One approach is to apply frequent re-initialization to the meteorological variables (e.g., temperature, specific humidity, and wind speed), which is widely used in the Air Quality Model Evaluation International Initiative (AQMEII) project. For example, Forkel et al. (2015) used the WRF-Chem model with a 2-day cyclic re-initialization of meteorological fields, which resulted in seasonal mean solar radiation and temperature decreasing by 20 W m^{-2} and 0.25 °C, respectively, due to the aerosol direct effects during the 2010 Russian summer wildfire episode. Applying the same model, Wang et al. (2015) found that the overall aerosol effects on the net surface solar radiation and 2-m temperature would be −16.2 W m^{-2} and -0.05 °C, respectively, over North America for July 2006. Although this approach can improve meteorology, abrupt changes at the end of each re-initialization period and consequent model spin-up result in discontinuity in the simulation of meteorological fields. Additionally, frequent re-initialization could dampen the feedback from the aerosol-radiation system. Alternatively, another common approach is to use nudging to produce better meteorology for air quality simulations (e.g., Vautard et al., 2012; Hogrefe et al., 2015), which is also used in many integrated models to study the aerosol-radiation interactions. For example, by using the WRF-Chem model with analysis nudging, Kumar et al. (2014) found that the radiative perturbation due to dust aerosols is about -2.9 ± 3.1 W m^{-2} at the top of the atmosphere, 5.1 ± 3.3 W m^{-2} in the atmosphere, and -8.0 ± 3.3 W m^{-2} at the surface, based on the sub-region averages in northern India. Using the WRF-CMAQ model with analysis nudging, Hogrefe et al. (2015) found that decreases of $PM_{2.5}$ between 2006 and 2010 resulted in simulated increases of summer mean clear-sky shortwave radiation between 5 and 10 W m^{-2}. One limitation of this approach is that nudging could dampen the feedback from the aerosol-radiation system. Although most studies acknowledge this limitation, many do not quantify the impacts from nudging and aerosols separately. In a one-month simulation of a sensitivity test (e.g., with/without nudging or aerosol direct feedback) with frequent model re-initialization, Hogrefe et al. (2015) determined that a weak nudging can slightly improve the representation of domain averages of 2-m air temperatures for retrospective air quality applications without overwhelming the simulated feedback effects. This result is expected because of frequent re-initialization used in the simulations. However, it is not clear how their selection of weak nudging impacted free atmospheric prognostic fields (e.g., temperature, mixing ratio, and cloud fields) and what would be the outcome if their model was run in a continuous mode without any re-initialization. But, they stated that additional tests are needed to quantify these two competing forces (nudging vs aerosol direct effects). When an integrated or coupled model is continuously run without any re-initialization and nudging, 2-m temperatures, as well as free atmospheric parameters, can be affected largely at local scales, although this aspect has also not been studied or documented in the literature. Weak coefficients used for tropospheric nudging by Hogrefe et al. (2015) are the same as those suggested by Bullock et al. (2014). However, Bullock et al. (2014) documented advantages and disadvantages of using such weak coefficients in their large spatial and time scale study. They found that stronger nudging coefficients minimizes modeling errors, but strong nudging might dominate over model forcing by various physical processes. However, weaker nudging coefficients led to mixed results - errors in temperature fields were still contained while moisture errors were not. One likely issue with using weak nudging coefficients is that for pristine and less polluted regions and/or periods when cloud processes remove pollution, reduced or weaker nudging coefficients can lead to increased integrated or coupled model errors.

Due to the uncertainties inherent in the regional climate modeling systems, model simulations (e.g., temperature) may drift from observed climate without using a nudging methodology. For example, several decadal regional climate simulation studies reported that without interior nudging, biases in monthly 2-m temperature can be greater than 4 K over the continental U.S. (e.g., Otte et al., 2012). These studies also reported that seasonal surface precipitation is more accurately simulated when a nudging methodology is applied (Bowden et al., 2013). Several studies have also demonstrated that nudging is required to develop credible climate simulations (Jöckel et al., 2006; Zhang et al., 2014). To further improve retrospective modeling simulations, indirect soil moisture nudging methods (e.g., Mahfouf, 1991; Hogrefe et al., 2015) as well as direct nudging methods for improving surface air temperature and moisture coupled with indirect nudging of soil temperature and moisture (e.g., Alapaty et al., 2008, 2016) have been developed in recent years.

Nudging of atmospheric temperature, though artificial, could compete with that of temperature changes induced by radiatively active and hygroscopic short-lived tracers. Since the associated radiative impacts due to nudging were included in many integrated (online coupled) meteorology-air quality models (here after referred to as integrated models), it poses two intriguing dilemmas: when nudging is continuously applied, what are the relative sizes of these two radiative forces (i.e., temperature changes due to nudging vs. temperature changes due to aerosol effects) at regional and local scales? How do these two forces present in the free atmosphere differ from those present at the surface? This work addressed these important questions by converting model simulated temperature tendencies due to nudging into radiative effects, referred to as pseudo radiative effects (PRE), through performing seasonal regional climate simulations for the central and eastern U.S. using the Weather Research & Forecasting (WRF) model. Reasons for not using an integrated model in this study are two-fold: (1) to clearly demonstrate whether or not a coupled model is truly needed for regional climate simulations; and (2) aerosol radiative effects were already quantified by using several measurements, as well as global and regional coupled models. Therefore, in this work, reported sizes of aerosol radiative effects were collected and compared with PRE due to nudging obtained from using the WRF model. Our rationale is further discussed in the next section.

2. Methodology

In this work, tropospheric nudging and surface nudging are used in the continuous WRF model simulations. The Four-Dimensional Data Assimilation (FDDA, Stauffer and Seaman, 1990, 1994) method has been widely used for tropospheric nudging. This method was demonstrated to reduce simulated meteorological biases, and has been applied for many air quality studies (Godowitch et al., 2011; Gilliam et al., 2012). To reduce surface biases in meteorological predictions, flux-adjusting surface data assimilation system (FASDAS) was developed by Alapaty et al. (2008, 2016) to provide continuous adjustments for three