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Diurnal and seasonal variability of $PM_{2.5}$ and AOD in North China plain: Comparison of MERRA-2 products and ground measurements

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ABSTRACT

North China Plain (NCP) is one of heavily polluted regions that is characterized by a mixture of a myriad of anthropogenic and natural aerosols. A substantial spatial and temporal variations of aerosols and their compositions there poses a good testbed for the validation of model simulations. Aerosol optical depth (AOD) and $PM_{2.5}$ (particulate matter with aerodynamic diameter < 2.5 μm) concentration products from the Modern Era Retrospective-Analysis for Research and Applications, version 2 (MERRA-2) are evaluated using available independent ground-based in situ and remote sensing products in the NCP. The comparison of MERRA-2 aerosol species to the observations is also performed. Although several satellite and ground-based AOD products are assimilated into the MERRA-2, MERRA-2 AOD is systematically smaller than independent sunphotometer measurements. The biases range from 0.09 (13%) in the summer to 0.17 (33%) in the spring and show little spatial dependence. Daytime AOD variations are captured by the MERRA-2, although MERRA-2 has relatively lower AOD. MERRA-2 produces lower $PM_{2.5}$ concentration relative to surface measurements in all seasons except in summer. The largest bias is found in the winter (44 $\mu g m^{-3}$). On the contrary, summer MERRA-2 $PM_{2.5}$ is close to surface-measured $PM_{2.5}$ (with bias of 0.4 $\mu g m^{-3}$). MERRA-2 was unable to reproduce diurnal $PM_{2.5}$ variation. Evaluation of MERRA-2 aerosol species in the winter of 2014 suggests that MERRA-2 could not keep track of dramatic day-to-day variation of aerosols and their species. Potential causes for this deficiency may include a lack of nitrate aerosols (accounting for 20% of $PM_{2.5}$ concentrations during heavily polluted days). This fault cannot be remedied by assimilation of satellite AODs because they are often missing.

1. Introduction

A large spread of haze, as a result of huge emission of particulate matter (PM) from industrial and agricultural activities and adverse weather condition in East Asia, results in significant impacts on environment, climate and human health (Li et al., 2016). More specifically, particles with an aerodynamic equivalent diameter smaller than 2.5 μm ($PM_{2.5}$) are of greatest health concern because they can pass through the nose and throat and be absorbed deep inside the lung. The smaller the particles, the deeper they can penetrate the respiratory system and the more hazardous they are to breathe (Valavanidis et al., 2008).

$PM_{2.5}$ shows a substantial spatiotemporal variability partly due to its short lifetime in the atmosphere. Fully understanding of spatiotemporal variability of $PM_{2.5}$ requires multiple approaches. Surface measurement is the fundamental requirement for monitoring $PM_{2.5}$, which is often taken to be the ground truth to validate satellite retrievals and model simulations. However, surface measurements are generally taken in populated regions and thereby their spatial coverage is limited. Therefore, detection of large-scale spatial distribution of $PM_{2.5}$ requires extra methods. Satellite retrievals and model simulations are two most promising methods in the production of regional to global

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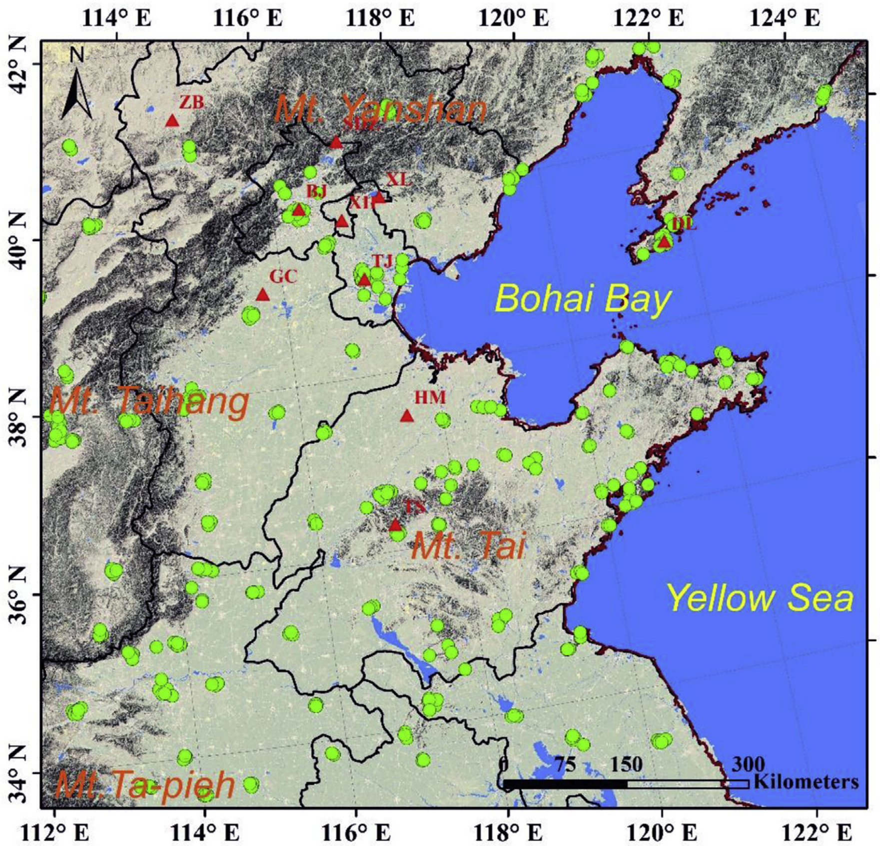

Fig. 1. Topographic maps of the NCP overlaid by 81 MEC $PM_{2.5}$ stations (blue circle) and 10 sun-photometer stations (red triangle). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

$PM_{2.5}$ distribution. Much progress has been made on these two aspects during the last decade, which are benefited from rapid development of satellite missions. For example, the MODerate resolution Imaging Spectroradiometer (MODIS) onboard Terra (1999) and Aqua (2002) can produce global aerosol optical depth (AOD) data with a spatial resolution of 3–10 km (Levy et al., 2013). Surface and satellite remote sensing of AODs were widely used to estimate $PM_{2.5}$ concentration (Wang and Christopher, 2003; Fu et al., 2018). Satellite AODs have also been assimilated into models that greatly enhances models' capability in the reproduction of aerosol distribution. One of examples is that the National Aeronautics and Space Administration (NASA) has extended the Modern-Era Retrospective Analysis for Research and Application, version 2 (MERRA-2) with an atmospheric aerosol reanalysis. MERRA-2 is based on a version of the Goddard Earth Observing System Data Assimilation System version 5 (GEOS-5) model driven by the MERRA meteorological reanalysis (Rienecker et al., 2011; Randles et al., 2018; Buchard et al., 2018). GEOS-5 is radiatively coupled to the Goddard Chemistry, Aerosol, Radiation and Transport (GOCART) aerosol module that produces five particulate species, i.e., sulfate, organic carbon (OC), black carbon (BC), mineral dust and sea salt. An important feature of the MERRA-2 is that it assimilates bias-corrected AOD from MODIS and the Advanced Very High Resolution Radiometer instruments. Additionally, Non-bias-corrected AOD from the Multiangle Imaging SpectroRadiometer over bright surfaces and AOD from Aerosol Robotic Network (AERONET) sunphotometer stations are newly assimilated in the MERRA-2. The data can be used to study the impact of aerosols on the atmospheric circulation, climate, and air quality around the world for its global and constant coverage and its distinction of aerosol species (Buchard et al., 2016, 2018).

MERRA-2 has potential to provide improved estimates of AOD and $PM_{2.5}$ compared to the model alone and with much greater coverage than surface observations. One of outstanding features of MERRA-2 is that it assimilates satellite AOD, which could likely constrain the total column aerosol mass in MERRA-2. Comparison of MERRA-2 $PM_{2.5}$ products against surface measurements over Africa, South America, Central and Eastern Asia showed that assimilation of satellite AOD did contribute to improvement of MERRA-2 $PM_{2.5}$ reanalysis (Buchard et al., 2016 and references therein). Discrepancies between the MERRA-2 and surface measurements were also revealed, for example, the lack of nitrate emissions in MERRA-2 and an underestimation of carbonaceous emissions in the Western US led to the reanalysis bias in $PM_{2.5}$ (Buchard et al., 2018).

The North China Plain (NCP) is one of heavily polluted regions in the world. NCP is recognized for its large-scale biomass burning of field residues in crop harvest season, occasional large spread of dust events in spring, frequent regional haze all year round because of large anthropogenic emissions (Xia et al., 2013). Therefore, the NCP poses a good testbed for the evaluation of MERRA-2 aerosol products, which becomes possible by much progress in surface observations of aerosols during recent years. A regional network of surface measurement of hourly $PM_{2.5}$ concentration has been established in 2013. Sunphotometer network has be expanded and accumulated more than ten years data in some stations (Che et al., 2014; Xia et al., 2016). These observations provide independent data to compare MERRA-2 aerosol products.

The objective of this study is to evaluate MERRA-2 aerosol products in the NCP. Since this region is characterized by a very complicated mixture of natural and anthropogenic emissions that poses a big challenge for the reanalysis, a thorough validation of MERRA-2 aerosol products in this heavily polluted region would indicate the way to improve aerosol reanalysis. The focus of this study is whether MERRA-2 can reproduce diurnal and seasonal variabilities of AOD and $PM_{2.5}$