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Estimation of Nighttime Aerosol Optical Depths Using the Ground-based Microwave Radiometer

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Abstract

Aerosol optical depth (AOD) is a crucial parameter for understanding the impact of aerosols on Earth's atmosphere and air quality. However, existing remote sensing methods mostly rely on the shortwave spectrum, which does not allow measurements at nighttime. In this study, we made a first attempt to retrieve AOD from ground-based microwave radiometer (MWR) measurements. Brightness temperatures (BT) at the K band (from 22.23 GHz to 30.00 GHz) and V band (from 51.25 GHz to 58.80 GHz) are trained against daytime spectral AOD from sun-photometer measurements together with temperature profile using the random forest regression (RFR) retrieval model, and the model is then used to retrieve nighttime AOD. The algorithm demonstrates satisfactory performance, with strong agreements with lunar AOD retrievals. The results also reveal a distinct day-night cycle of AOD, with nighttime AOD typically higher than its daytime value. The physical basis of our approach is verified using vertical temperature and humidity profiles from sounding observation and simulation results from WRF-Chem as well as the MonoRTM. Our study provides an effective and convenient approach to estimate nighttime aerosol loading from surface, which has great potential in environmental monitoring and climate forcing research.

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1. Introduction

Aerosols have a significant impact on weather patterns and the Earth's climate (Huang et al., 2014; Li et al., 2022; Li et al., 2019; Riemer et al., 2019), offsetting about one-third of the warming effect by anthropogenic greenhouse gases and influence large-scale circulation (Huang et al., 2014; Li et al., 2022). However, accurately assessing their role in radiative forcing is a major challenge (Fan et al., 2016; Ghan et al., 2016; Seinfeld et al., 2016). Monitoring aerosol optical depth (AOD) is crucial for understanding aerosol impacts on climate and air quality, as it reflects the total amount of aerosols in the atmosphere optically (Visioni et al., 2023; Yang et al., 2020). As a result, there have been extensive efforts to measure AOD by various methods.

Remote sensing, either ground based or space borne, is an effective way to retrieve column AOD (Chaikovsky et al., 2020; Mhawish et al., 2017; Omar et al., 2013; Sinyuk et al., 2020). Other observations measure physicochemical properties of aerosols instead of optical properties like AOD (Kremser et al., 2016; Li et al., 2016b). Mainstream aerosol remote sensing techniques rely on aerosol scattering of shortwave radiation in the ultraviolet and/or visible spectrum, thus only daytime AOD can be obtained (Sayer et al., 2019; Sun et al., 2021). However, aerosols typically have day-night variability, due to factors such as different emission sources, boundary layer structure, etc (Arola et al., 2013; Cachorro et al., 2004; Cachorro et al., 2008; Guo et al., 2017). Aerosols at nighttime also have detectable impacts on the radiative balance, since they usually exert a warming effect in contrast to the cooling effect at daytime (Chen and Zhao, 2024; Colarco et al., 2014; Zhang et al., 2022), particularly in polar regions with the rapid change of AOD between daytime and nighttime (Chen and Zhao, 2024; Stenchikov et al., 2002; Wei et al., 2021). In special cases such as aerosols above the open oceans, they consistently exert a cooling influence in both shortwave and longwave, yet for dust aerosols, they potentially exert a warming effect

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in longwave during both day and night (Adebiyi et al., 2023; Feng et al., 2022; Song et al., 2022).

Remote sensing of aerosol properties at night is a challenging task. Lunar photometer emerges during recent years as an effective and relative accurate nighttime AOD retrieval technique, and has been widely used within the Aerosol Robotic Network (AERONET) (Barreto et al., 2016). However, this method can only provide data at ~ halftime each month since it requires a relatively large amount of moon-reflected solar radiation (Barreto et al., 2017; Berkoff et al., 2011). Compared with lunar photometer method, the star photometry provides reliable nighttime AOD measurements by leveraging stellar irradiance, eliminating lunar phase corrections, with long-term datasets revealing diurnal aerosol dynamics (Pérez-Ramírez et al., 2011; Pérez-Ramírez et al., 2016; Pérez-Ramírez et al., 2008; Pérez-Ramírez et al., 2015). Arctic deployments and further development such as using a wide-field imager enhance its adaptability in extreme environments and spatiotemporal resolution, addressing gaps in traditional sun-photometer-based nocturnal monitoring (Ebr et al., 2021; Ivanescu et al., 2021; Ivanescu and O'neill, 2023). Other researches take advantage of urban light to retrieve nighttime AOD from space from multiple sensors (Jiang et al., 2022; Meng et al., 2023; Wang et al., 2023; Wang et al., 2020; Zhou et al., 2021). For example, Zhang et al. examined the effectiveness of retrieving nighttime AOD over urban areas by utilizing city lights observed through the VIIRS (Visible Infrared Imaging Radiometer Suite) Day-Night Band (DNB) (Zhang et al., 2019). However, this approach has limitations as it does not account for multiple scattering and gas absorption, which can potentially reduce the signals from aerosols (Zhou et al., 2021). Furthermore, these studies are constrained to the spatial scale of urban areas, resulting in vast rural regions being unexplored (Meng et al., 2023). Active remote sensing, such as lidars, can provide aerosol measurements at both day and night time (Balmes et al., 2021; Jiang et al., 2024). Nonetheless, solving the lidar equation requires assumption of the lidar ratio, and this assumed lidar ratio often

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causes large uncertainty of the retrieved extinction profiles as well as column integrated AOD usually (Liu et al., 2018; Rogers et al., 2014; Santa Maria and Winker, 2005). For the day-night difference of AOD, previous studies find slight increases of nighttime AOD using the long-term sun-and-star photometry data (Pérez-Ramírez et al., 2012; Pérez-Ramírez et al., 2016; Wang et al., 2004). Moreover, using Infrared Atmospheric Sounder Interferometer (IASI) and Cloud-Aerosol Transport System (CATS) are also effective methods to understand day-night differences in dust aerosols (Tindan et al., 2023; Yu et al., 2021). However, existing research regarding day-night difference of AOD only focuses on special types of aerosols such as dust aerosols, and has low availability due to the moon phase and urban light extent (Barreto et al., 2017; Jiang et al., 2022; Meng et al., 2023; Wang et al., 2023; Wang et al., 2020; Zhou et al., 2021). Due to our limited capability to measure nighttime AOD, there is a significant knowledge gap between daytime and nighttime aerosol properties.

In contrast to shortwave radiation which is only available during daytime, longwave radiation, especially in the thermal infrared and microwave spectrum, exists during both day and night, and offers the potential to derive nighttime aerosol property (Dufresne et al., 2002; Panicker et al., 2008). Previous research has explored the possibility to retrieve aerosol loading using longwave measurements, but mostly focused on large particles such as dust (Clarisse et al., 2019; Desouza-Machado et al., 2010; Klüser et al., 2012; Pierangelo et al., 2004; Pierangelo et al., 2005; Zheng et al., 2022; Zheng et al., 2023). For example, using collocated thermal infrared observations from MODIS and dust optical depth from Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), Zheng et al. simultaneously retrieve the thermal infrared dust optical depth and coarse-mode effective diameter over global oceans (Zheng et al., 2023). Observational and simulation studies indicate that the microwave brightness temperatures (BTs) and brightness temperature polarization differences may be both useful for estimating the dust mass loading (Ge et al., 2008; Hong et al.,

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2008; Huang et al., 2007; Mitra et al., 2013). Our previous study utilized satellite-based thermal infrared measurements in the atmospheric window region to retrieve nighttime AOD (Liu et al., 2024), and proves the effectiveness of these longwave measurements in deriving aerosol properties.

Ground-based microwave radiometer (MWR) is a widely used remote sensing instrument to retrieve temperature and humidity profiles using emitted longwave radiation by the surface-atmosphere system (Bianco et al., 2005; Greenwald et al., 2018; Knupp et al., 2009). Considering the aforementioned concepts of utilizing longwave radiances to retrieve aerosol properties and the potential alterations in microwave BTs due to the modified temperature and humidity profiles resulting from the shortwave radiation effect of aerosols, there is potential that aerosol information can be derived from MWR measurements. Therefore, in this study, we explore the possibility to retrieve AOD using surface based MWR measurements in the K spectral bands (22.23 GHz, 22.50 GHz, 23.03 GHz, 23.83 GHz, 25.00 GHz, 26.23 GHz, 28.00 GHz, and 30.00 GHz) and V spectral bands (51.25 GHz, 51.76 GHz, 52.28 GHz, 52.80 GHz, 53.34 GHz, 53.85 GHz, 54.40 GHz, 54.94 GHz, 55.50 GHz, 56.02 GHz, 56.66 GHz, 57.29 GHz, 57.96 GHz, and 58.80 GHz). A machine learning based algorithm is developed to estimate AOD during both day and night. The theoretical basis of the method is further verified using regional model and radiative transfer simulations. The difference between day and night time AOD is also examined using the retrieval results.

2. Data and Methods

The retrieval algorithm used in this study is described in Figure 1 and includes four main steps: (1) preprocessing of input variables, (2) training the Random Forest Regression (RFR) retrieval model, (3) estimation of AOD using the trained model, and (4) independent validation to refine the model and assess its performance

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compared to lunar photometer observations. The details of the datasets and methods are explained below.

2.1 Datasets

In this study, we utilized BT data collected from the MP-3000A MWR, which was stationed at the Beijing Nanjiao Meteorological Observatory located in China (39.80°N, 116.47°E). The MP-3000A MWR is capable of detecting signals in the K-band (22 to 30 GHz) and V-band (51 to 59 GHz), and it is also equipped with additional features such as a precipitation sensor, an infrared radiation thermometer, and other relevant instruments. To maintain the accuracy and consistency of the atmospheric BT measurements, the MWR undergoes regular real-time calibration. These measurements are essential for obtaining temperature profiles and AOD data. Our analysis focuses on the K and V band of BT observations with 22 available channels, because BT observations at the K band are sensitive to water vapor absorption and BT observations at the V band are sensitive to oxygen absorption and temperature changes. We use the data ranging from December 2019 to October 2020 with a temporal resolution of one minute.

The measured BTs include inaccuracies and unusual values caused by instrumental faults, calibration problems, and environmental factors. Hence, it's crucial to conduct quality control (QC) checks on the BT data before processing it further. These checks involve removing abnormal values to ensure that the BTs fall within a reasonable temperature range of 2.7 to 330 Kelvin, and inspecting for data consistency over time as per the methodology of Zhang et al. (Zhang, 2024). Notably, because the collocation between MWR and Level 2 sun photometer AOD products from the AERONET is already clear-sky data, there is no need to perform cloud screening on the MWR data.

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AOD retrieved using the solar and lunar methods at the Beijing-CAMS AERONET site, which is the closest site to the MWR location, is used as training and validation data in the retrieval algorithm. For training our model, we utilized Level 2 sun photometer AOD products at the wavelengths of 440nm, 675nm, 870nm, and 1020nm during the day. Version 3 Level 1.5 lunar AOD products at the same wavelengths to validate AOD retrievals at night.

Given that MWRs are instrumental in tracking atmospheric temperature and humidity profile changes (Zhang et al., 2024), our method retrieves vertical temperature profiles concurrently. This is achieved by using temperatures at different pressure levels obtained from the European Center for Medium-Range Weather Forecasts (ECMWF) Reanalysis version 5 (ERA-5) as the target for our training. To further assess the accuracy of the model in predicting vertical temperature profiles, we utilized the collocated sounding data obtained from Beijing Meteorological Station (station ID: 54511) during the corresponding time frame. These sounding data were collected twice daily respectively at 0000 and 1200 UTC from December 2019 to October 2020. For the physical interpretation of our retrieval method, we employed collocated vertical profiles of temperature and relative humidity (RH) from the same sounding data under varying aerosol loadings to explore the effects of aerosol loading on the vertical profiles of meteorological variables. These vertical profiles were further utilized to compute BTs using the monochromatic radiative transfer model (MonoRTM).

2.2 Retrieval Algorithm

Because the relationship between aerosol loading and microwave radiation is complicated and could be nonlinear, we use a machine learning based retrieval method focusing on the RFR method (Svetnik et al., 2003). All variables are appropriately matched in both space and time. Specifically, AOD from sun photometer measurements and BTs from the MWR are matched within a 5-minute

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time window, while hourly temperature profiles from ERA-5 reanalysis datasets and BTs from the MWR are collocated within a 30-minute time window and a 15 km spatial radius.

We first apply the relative importance feature selection technique, which is based on the Gini importance measure (Nembrini et al., 2018), to identify significant independent variables and build a generalized model. The relative importance of each factor is presented in Figure 2. It is observed that BTs across various frequency bands carry similar levels of importance, suggesting that the BTs are almost equally important for retrieving AOD.

Subsequently, the retrieval algorithm is trained using eight selected K-band BTs as input and target variables, which include sun photometer AOD at 440nm, 675nm, 870nm, and 1020nm, as well as ERA-5 vertical temperature profiles at 100 hPa, 200 hPa, 500 hPa, 700 hPa, 850 hPa, and 1000 hPa. To ensure the representativeness of the sampling, we select the first 3/4 of the data in each month as the training set and the last 1/4 of the data as the testing set. Additionally, the algorithm is adapted to estimate nighttime AOD using nighttime BTs from microwave radiometry as inputs, which is then validated against nighttime AOD observations from lunar measurements in lunar photometer for the same period. Moreover, AOD, whether in the visible or microwave region, is associated with aerosol loading, which serves as the foundation for retrieving visible AOD using microwave observations. Since we primarily aim at retrieving AOD rather than aerosol type, we did not consider AOD at the other wavelengths when building the AOD retrieval model. The relationship between AOD at 550nm and that at the microwave band is enclosed in the random forest model. The model performance is assessed against photometer retrievals using metrics such as linear regression slope and intercept, correlation coefficient (R), root-mean-square error (RMSE), and mean absolute percentage error (MAPE).

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The RFR model is built by varying the number of decision trees from 8 to 256. Through validation analysis, it is determined that the optimal number of trees is 128, based on the best performance during validation. After refining the algorithm through extensive training and testing, it is used to retrieve nighttime AOD from nighttime MWR BTs, with validation against collocated lunar AOD measurements from the lunar photometer. Moreover, before investigating the diurnal cycle of MWR derived AOD, we perform a quality control on the minute-resolution retrieval results that typically have a higher noise level. Specifically, for each specific minute, we extract the AOD for this minute from each day to form an AOD sequence. We then calculate the mean and standard deviation of this AOD sequence. Finally, we remove AOD that exceeds three times the standard deviation. Considering the suitable quantity of outliers procured by setting the threshold at three standard deviations and the prevalently utilized 3-sigma rule, we used three standard deviations as the threshold (Li et al., 2016a; Liu et al., 2024; Wang et al., 2012).

2.3 WRF-Chem simulations

To investigate the effect of aerosols on downward microwave radiation, we use the Weather Research and Forecasting model with Chemistry (WRF-Chem) simulations combined with the MonoRTM radiative transfer model. Because MWR-observed BT change is not only due to AOD change but also reflects the change of meteorological conditions due to the AOD change, we apply WRF-Chem and MonoRTM radiation transfer model instead of radiative transfer simulations only.

WRF-Chem simulation runs from 0000 UTC on 17 December 2016 to 0000 UTC on 20 December 2016 (a 72-hour period). The simulation period is different from that of the retrieval because there are no updated emission fields for 2019 and 2020. The initial meteorological conditions used for the simulations are based on the National Center for Atmospheric Research (NCEP) Final Global Forecast System Operational Analysis (FNL) provided by the National Oceanic and Atmospheric Administration

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(NOAA), with a 1° × 1° spatial resolution and a 6-hour temporal interval. The emission fields used here are Emissions Database for Global Atmospheric Research (EDGAR), MIX, and Multi-resolution Emission Inventory for China (MEIC) (Crippa et al., 2018; Li et al., 2017; Wang et al., 2014). The surface emissivity we used for simulation is the default data for WRF-Chem. The simulation domain encompasses the area of Beijing, Tianjin, and Hebei province (as shown in Figure 3), with a center point at 40.00°N, 116.25°E. The model employs a three-tiered nesting configuration, featuring outer grids of 40 × 46 with a 90 km horizontal spacing, middle grids of 48 × 60 with a 30 km horizontal spacing, and inner grids of 51 × 72 with a 10 km horizontal spacing. The vertical atmosphere is segmented into 47 levels, ranging from the model's ground level to 100 hPa, encompassing both the surface and the upper atmosphere. Figure 3 illustrates the domains of the WRF model simulations and the location of the MWR deployed at the Beijing Nanjiao Meteorological Observatory in China. To further confirm our findings, we perform another set of parallel experiments lasting from 0000 UTC on 3 December 2016 to 0000 UTC on 5 December 2016 (a 48-hour period) with the same settings. The first day of both sets of experiments is used for model stabilization, and the subsequent days are utilized for analysis.

For the choices of physical parameterization schemes, we employ the Lin microphysics scheme, the rapid radiative transfer model for global climate model (GCM) applications (RRTMG) for shortwave radiation, the Yonsei University (YSU) boundary layer scheme, the Monin-Obukhov ground layer scheme, the Carbon-Bond Mechanism version Z (CBM-Z) for gas-phase chemistry, and the Model for Simulating Aerosol Interactions and Chemistry (MOSAIC). The model output has a one-hour temporal resolution.

To investigate the responses of surface downward microwave radiation to aerosol loadings, we also conducted two parallel experiments with and without aerosol

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emissions in the study. Two simulations that are respectively, designated as "EXP_AER" and "EXP_NOAER" are carried out. The EXP_AER experiment is defined as a control simulation in which aerosol and aerosol precursor emission scheme is turned on. This aerosol emission includes emissions of carbon monoxide, nitrogen oxides, sulphate oxides, dust aerosols, biomass aerosols, biomass burning aerosols, sea salt aerosols and anthropogenic aerosols. The sensitivity experiment ("EXP_NOAER") is also conducted by closing corresponding aerosol and aerosol precursor emission scheme. The difference between control and sensitivity results are considered as the adjustments of vertical meteorological profiles to aerosol loadings. This method is also widely used to explore the radiative forcing of different kinds of aerosol and its effects on meteorological fields in previous studies (Chen et al., 2023; Matsui et al., 2018).

It is important to note that the aerosol-radiation interaction feature is activated in the WRF-Chem model to investigate the impact of aerosol loadings on meteorological fields. Subsequently, we input meteorological profile data from pollution cases without cloud cover at each grid point into the monochromatic radiative transfer model (MonoRTM) to calculate the corresponding BT responses at various frequencies within the K-band.

2.4 MonoRTM

The MonoRTM, developed by Atmospheric and Environmental Research (AER), is a radiative transfer model specifically designed for microwave and millimeter-wave applications (Clough et al., 2005). This model is particularly useful in the microwave radiation calculation (Payne et al., 2011). In this study, it is used to calculate the brightness temperatures (BTs) associated with the simulated temperature and humidity vertical profiles from WRF-Chem.

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3. Results

3.1 Model fitting and validation

The retrieval model has great fitting performance, as shown by Figure 4. The model fitting reaches correlation coefficients of 0.98 for the 440 nm, 675 nm, 870 nm, and 1020 nm, respectively, albeit with a minor systematic low bias for high AOD scenarios, which is similar to MODIS AOD products (Levy et al., 2013). Due to the consistent model performance in all wavelengths (Figure 4), we will focus on results at 440 nm in the following discussions.

Figure 5 displays the comparison between the daytime and nighttime AOD independently retrieved by MWR using our algorithm and those from the sun and lunar photometer from December 2019 to October 2020. The model, tested during the daytime, utilized a dataset of over 3,000 samples and achieved correlation coefficients of 0.96 for 440 nm (Figure 5a). Most points are concentrated on the 1:1 line, with RMSE within 0.11 and MAPE within 0.11. The accuracy of this estimation is similar to existing shortwave-based algorithms (Levy et al., 2013). However, the key advantage of using microwave BT is the capability to retrieve AOD at night, a feature lacking in these shortwave-based algorithms (Figure 5b). Nighttime AOD retrieval reaches comparable performance to that for daytime, exhibiting a high correlation of 0.91 with lunar AOD. A minor systematic bias towards lower values in high AOD scenarios is also noted, with RMSE about 0.14 and MAPE approximately 0.28, indicating the overall satisfactory performance of MWR retrievals. In addition, the MWR results also well capture the spectral variation of AOD for fine (440 nm to 870 nm Angstrom index > 1) and coarse mode particles (440 nm to 870 nm Angstrom index < 1), as shown in Figure 6.

Our algorithm simultaneously retrieves daytime and nighttime temperature profiles. As shown in Figure 7 & Figure 8, atmospheric temperature retrieval results also

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demonstrate good performance and exceed those of AOD. This is expected since the main signals in the microwave come from emitted radiation by the atmosphere that is directly related to temperature. In detail, R is generally above 0.98 and all of the RMSEs are around 1.0 K in the training set (Figure 7). Similarly, for the test set, R is above 0.95 and all of the RMSEs are around 1.8 K the test set (Figure 8), comparable to previous studies using MWR data with an optimal estimation method (Cimini et al., 2006). The significant biases at some pressure levels may be attributed to the larger biases between sounding data and reanalysis data that is used to train the model (Varga and Breuer, 2022). Our model also well captures the characteristics of the climatological mean temperature vertical profile, with the error in each pressure layer within 1.5 K (Figure 9a). There exist greater RMSE and bias in low pressure levels partially due to the higher temperature variations in these levels, the overall RMSE and bias serve to illustrate the exemplary performance of the model in estimating the vertical temperature profiles (Figure 9b & c).

In summary, the day and nighttime MWR-based AOD and vertical temperature profiles derived from our algorithm successfully capture the AOD variability and vertical temperature profile characteristics with satisfactory accuracy. This model also unveils the spectral characteristics of AOD, with higher wavelengths corresponding to lower AOD. With great performance through model validation, we will investigate the diurnal cycle of AOD in the following section.

3.2 The diurnal cycle of MWR derived AOD

We further examine the day-night differences in the AOD retrieved by MWR and compare them to those revealed by surface photometer.

Figure 10a-b illustrates the mean diurnal cycles of the photometer AOD and MWR-based AOD derived from BT observations at the Beijing Nanjiao Meteorological Observatory in China. As shown in Figure 10a, mean diurnal AOD

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follows a bi-modal temporal distribution, with a greater peak ~21:00 and a secondary peak at ~03:00. The AOD stays relatively low from 06:00 to 10:00, gradually rises from 10:00 to 21:00, reaching the first peak at 21:00. After that greater peak, the AOD decreases from 22:00 to 00:00, and then increases again until it reaches the second peak at 03:00. This pattern is consistent across other spectral bands (675 nm, 870 nm, and 1020 nm, not shown here). Because the number of nighttime AODs from the photometer is smaller than that during the daytime, but the number of nighttime AODs from the MWR is nearly equal to that during the daytime, this decrease may not be entirely explained by the lack of data sampling and needs further investigation in the future study. Moreover, although the MWR-based AOD seems to underestimate the extreme pollutions with high AOD compared with photometer observation, since the number of upper outliers of AOD of the photometer is higher than that of MWR, the overall temporal pattern is similar to that of the photometer (Figure 10a).

The mean and median AOD values further support the above findings, highlighting higher nighttime AOD compared to daytime (Figure 10b). This difference is validated by the boxplots of MWR-based AOD and photometer AOD (Figure 10c), passing the Student's *t*-test significance test with $p \leqslant 0.05$. Specifically, the median daytime AOD is in the range of 0.15 to 0.28 for MWR and 0.15 to 0.27 for the photometer, while the median nighttime AOD is greater than 0.34 for MWR and higher than 0.30 for the photometer. Similarly, the mean daytime AOD is in the range of 0.25 to 0.35 for MWR and 0.24 to 0.32 for the photometer, while the mean nighttime AOD is greater than 0.40 for MWR and over 0.44 for the photometer. This discrepancy between daytime and nighttime AOD has also been observed in previous studies estimating nighttime AOD by incorporating infrared radiance measurement from AIRS into the machine learning model (Liu et al., 2024). Notably, the mean AOD tends to exceed the median AOD, partly due to the long-tail distribution of AOD and the presence of high extreme values (Sayer et al., 2019). Moreover, AOD at the other wavelengths (675 nm, 870 nm, and 1020 nm) exhibit similar diurnal patterns with

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peaks at about 20:00-22:00 (not shown here) and higher nighttime AOD in general (Figure 6).

The increase in nighttime AOD compared to daytime can be attributed to various factors, including a shallower mixed layer due to reduced horizontal mixing and transport, a decrease in atmospheric environmental capacity, higher relative humidity, enhanced aerosol hygroscopic growth, or intensified pollution emissions (Brock et al., 2016). Similar observations of elevated nighttime particle matter concentration have been reported in previous studies (Perrone et al., 2022; Su et al., 2023). However, research on nighttime aerosol properties is limited, warranting further analysis to fully understand these discrepancies, which exceeds the scope of this study.

In summary, by using the BT measured by the MWR to retrieve AOD during nighttime, we can uncover the daily cycle of AOD. This improves our understanding of the day-nighttime AOD variability, provides insights into the diurnal changes of atmospheric pollution and sheds light on nighttime aerosol radiative effects.

3.3 Physical interpretation

Since the machine learning technique does not necessarily represent the physical relationship between aerosol loading and microwave radiances, we further verify the theoretical basis of our technique by analyzing the observed temperature and RH profiles under various AOD levels and using WRF-Chem combined with MonoRTM simulations. A set of sensitivity experiments with and without aerosol forcing is conducted using WRF-Chem as described in Section 2, whose atmospheric profiles, including temperature, water vapor, gases and aerosols, are then used as the inputs to the MonoRTM to simulate the downward microwave radiances (represented by BT) observed by the MWR. To mitigate the influence of surface temperature on BT, we maintained a consistent surface temperature range (265 K-270 K) throughout the simulation.

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We first analyze the temperature and RH profiles from sounding observations under various AOD levels (Figure 11a-b & d-e). These AOD levels include light pollution (AOD<0.2), medium pollution (0.2<AOD<0.5), and heavy pollution (AOD>0.5) scenarios. The selection of this threshold is to ensure a balanced sample size for each scenario. All differences in the temperature and RH profiles under different AOD scenarios passed the significance test with $p \leqslant 0.1$ by the *t*-test. For the temperature profiles, a higher AOD corresponds to a lower temperature in the upper atmosphere, and vice versa (Figure 11a). However, for the low-level atmosphere, the temperature might first increase as AOD increases and then decrease with AOD as increases. This is associated with aerosol type and optical properties (Che et al., 2024; Mahowald et al., 2011). For the RH vertical profiles, RH increases as AOD increases at all pressure levels (Figure 11b). This may be attributed to aerosol hygroscopic growth effect, leading to a higher AOD (Quan et al., 2018). Notably, since the collocation between MWR and Level 2 sun photometer AOD products from the AERONET is already clear-sky data, the vertical profiles of RH is relatively low. BTs at 22.23 GHz calculated by these vertical profiles from MonoRTM also demonstrate that BTs tend to increase with AOD (Figure 11c). BTs at other frequencies in the K band also show similar trend (not shown here). Similarly, the WRF-Chem output also demonstrates the sensitiveness of temperature and RH vertical profiles to aerosol loading, contributing to statistically significant BT difference under different pollution levels (Figure 11d-f). The above observational evidence indicates that MWR estimate AOD by detecting the temperature and humidity profile differences caused by the presence of aerosols, further verifying the theoretical basis of our technique.

Furthermore, our simulation results, illustrated in Figure 12 and 13, indicate that for all frequencies in the K band, BT increases as AOD levels increase. This phenomenon exists in both the daytime and nighttime. Specifically, at 22.23 GHz, BT levels for clean conditions range from 60 K to 80 K, while for polluted conditions they range from 80 to 130 K, showing a statistically significant difference at both daytime and

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nighttime (Figure 12a & 13a). BT levels at other frequencies support this trend, indicating that BT tends to increase with AOD (Figure 12b-d & 13b-d). The increase of K band BT with AOD might be related to coherent changes of water vapor and aerosols, either due to aerosol absorption of water or meteorological conditions that affect both water vapor and aerosols. In contrast to the observations in the K band, an analysis of the V band frequencies reveals a consistent decrease in BT with the reduction of AOD levels, applicable to both diurnal and nocturnal periods (Figure 12e-h & 13e-h), which well corresponds to the cooling effect of aerosols. Notably, at a frequency of 51.76 GHz, the BT levels exhibit a range of 264 K to 270 K under pristine atmospheric conditions, whereas under polluted conditions, these levels are observed to be between 262 K and 265 K. Although the magnitude of this change is less pronounced than that observed in the K band, it still passes the statistical significance ($p \leqslant 0.1$ by the t-test), indicating a reliable and measurable effect. The above-mentioned conclusion was further verified by simulations lasting from 0000 UTC on 3 December 2016 to 0000 UTC on 5 December 2016 (a 48-hour period) with the same settings (not shown).

To deepen our understanding of the impact of aerosol loading on longwave radiation, we conducted a comparative analysis using WRF-Chem. By comparing scenarios with aerosol loadings (EXP_AER) and without aerosol loadings (EXP_NOAER), we examined the differences in AOD, surface temperature (ST) and ground downward longwave radiation (GDLR). The findings reveal that higher aerosol concentration levels have a negative effect on ST (Figure 14b & e), particularly during the daytime (Figure 14b), while positively influencing GDLR (Figure 14c & f), especially at nighttime (Figure 14f), which is consistent with the above MonoRTM calculations.

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4. Conclusions and Discussions

This study introduces a new method for estimating clear sky AOD using BT measurements in the K and V band obtained from the MWR. By establishing a strong correlation between the photometer AOD and multiple BTs derived from the MWR at the Beijing Nanjiao Meteorological Observatory using a machine learning algorithm, we were able to accurately retrieve nighttime AOD and vertical temperature profiles. This model also well captures the spectral characteristics of AOD with higher Angstrom index for fine-mode dominated AOD and lower Angstrom index for coarse-mode dominated AOD. After applying this model with satisfactory performance, we show that the AOD diurnal cycle and find that AOD values follow a bi-modal diurnal cycle temporal distribution, with a greater peak ~21:00 and a secondary peak at ~03:00, suggesting higher nighttime AOD compared with daytime. The difference between daytime and nighttime AOD observed in the MWR data well agrees with sun and lunar photometer observation as well as particle matter concentration observations.

The theoretical basis of our algorithm is also confirmed by analyzing observational vertical profiles of temperature and RH under various AOD levels and WRF-Chem as well as MonoRTM simulations. Observation indicated that the vertical profiles of temperature and RH have statistically significant differences ($p \leqslant 0.1$) under different AOD levels, suggesting that MWR might estimate AOD by detecting the temperature and humidity profile differences caused by various aerosol loadings. Simulation further indicated a consistent and mostly linear increase in BTs in the K band and decrease in BTs in the V band with AOD (550 nm) across all time periods. Aerosols tend to induce a cooling effect at surface while increasing ground downward longwave radiation, especially at the nighttime.

This study holds significant promise for environmental and climate research as MWR BT measurements can be obtained day and night without being hindered by bright

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surfaces. The methodology developed here can potentially be applied to MWRs in other locations worldwide to retrieve both daytime and nighttime AOD values. However, it is important to note that this investigation is preliminary and may contain uncertainties. It is also applicable under clear sky since during cloudy sky, the downward microwave radiation will be dominated by that emitted by clouds.

Moving forward, we aim to explore additional aerosol characteristics that may be inferred from BT measurements, such as aerosol absorption and layer height. This will enhance our understanding of aerosol distribution and properties, ultimately improving our ability to monitor and predict aerosol impacts on climate and the environment.

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Code and data availability

The sun photometer AOD data was obtained from https://aeronet.gsfc.nasa.gov/new_web/webtool_aod_v3.html, last access: 20 Apr 2024; the lunar photometer AOD data was obtained from https://aeronet.gsfc.nasa.gov/new_web/webtool_aod_v3_lunar.html, last access: 20 Apr 2024; the temperature profile from the ERA-5 reanalysis data was downloaded from https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=overview, last access: 24 Apr 2024; the MonoRTM source code is available on https://github.com/AER-RC/monoRTM, last access 18 Apr 2024. The sounding data obtained from Beijing Meteorological Station (station ID: 54511) was obtained from https://weather.uwyo.edu/upperair/bufrraob.shtml.

Author contributions

GL and JL conceived the study and wrote the original draft. GL, SY, LZ, and CZ ran the simulation and conducted the corresponding analysis. All authors revised and reviewed the draft.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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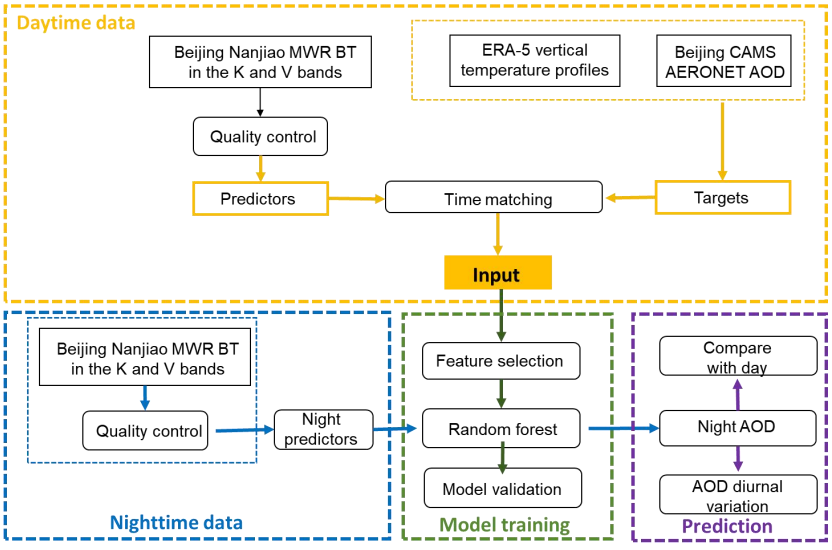

Figure 1. The flowchart for clear sky nighttime AOD retrieval algorithm.

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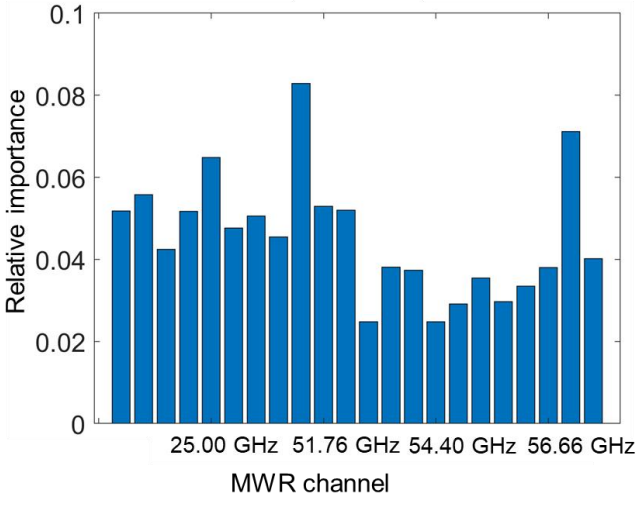

517

518 **Figure 2.** Relative importance of all BTs in different frequencies measured by MWR
519 in the RFR model. The vertical axis represents relative importance (unitless), and the
520 horizontal axis corresponds to different variable inputs (BTs in different frequencies
521 measured by MWR in the RFR model). These channels include K band (22.23 GHz,
522 22.50 GHz, 23.03 GHz, 23.83 GHz, 25.00 GHz, 26.23 GHz, 28.00 GHz, 30.00 GHz)
523 and V band (51.25 GHz, 51.76 GHz, 52.28 GHz, 52.80 GHz, 53.34 GHz, 53.85 GHz,
524 54.40 GHz, 54.94 GHz, 55.50 GHz, 56.02 GHz, 56.66 GHz, 57.29 GHz, 57.96 GHz,
525 58.80 GHz).

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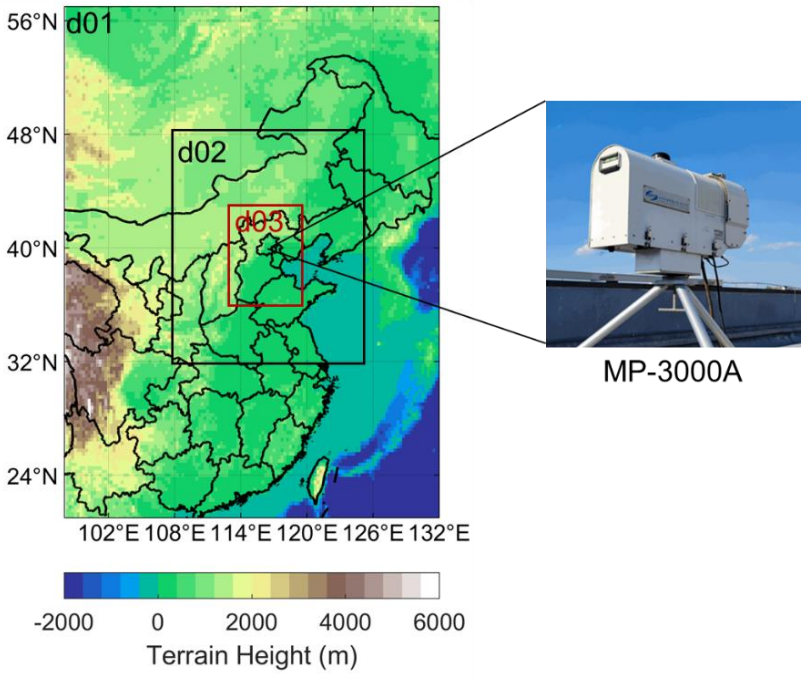

Figure 3. Simulation domains (left panel) of the WRF-Chem experiments. The MWR (right panel) used in this study is located in domain 3. This domain has a spatial resolution of 10 km. The MP-3000A MWR by Radiometrics is deployed at the Beijing Nanjiao Meteorological Observatory (39.80°N, 116.47°E) in China for brightness temperature (BT) measurements.

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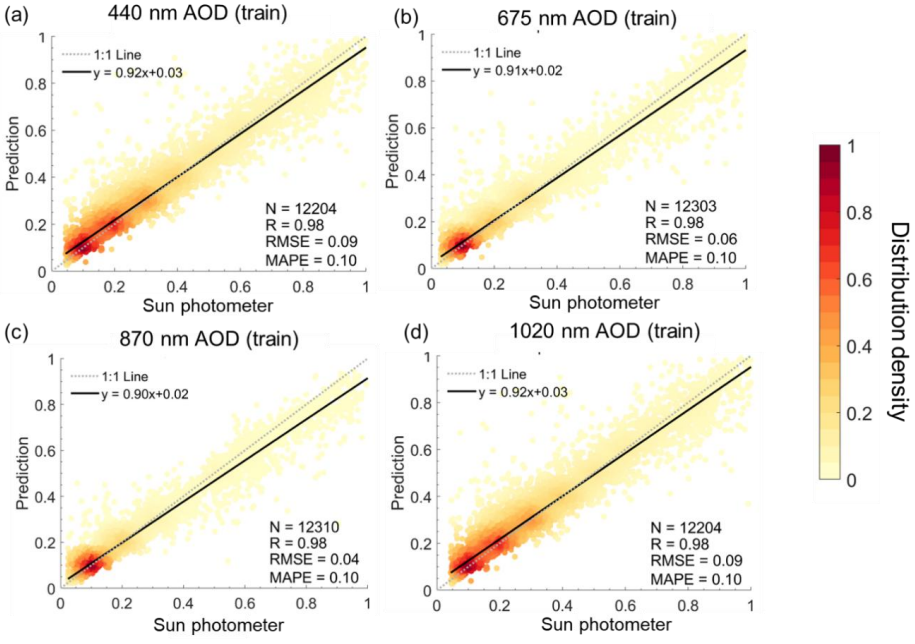

Figure 4. Density scatterplots of daytime AOD in the train set of MWR and sun photometer with (a) 440 nm, (b) 675 nm, (c) 870 nm, and (d) 1020 nm. The dashed dark gray line represents the 1:1 line, and the black solid line represents the linear regression line.

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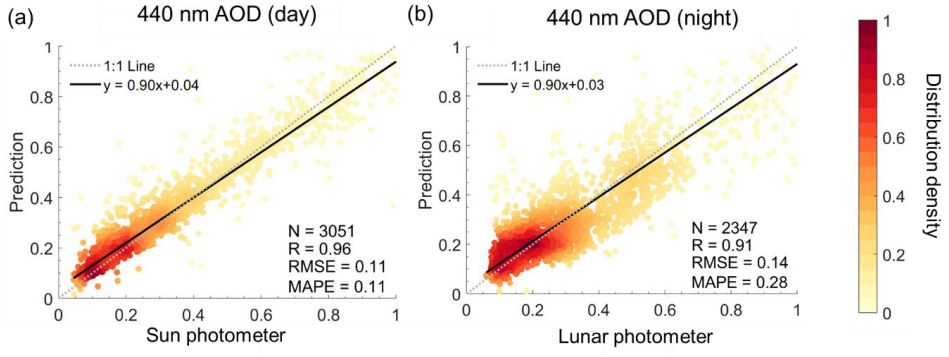

Figure 5. Density scatterplots of 440 nm AOD in the test set of MWR and the photometer with (a) daytime, and (b) nighttime. The dashed dark gray line represents the 1:1 line, and the black solid line represents the linear regression line. Note that the daytime corresponds to 6:00 am to 6:00 pm for the local time (UTC+8), and nighttime corresponds to the remaining time.

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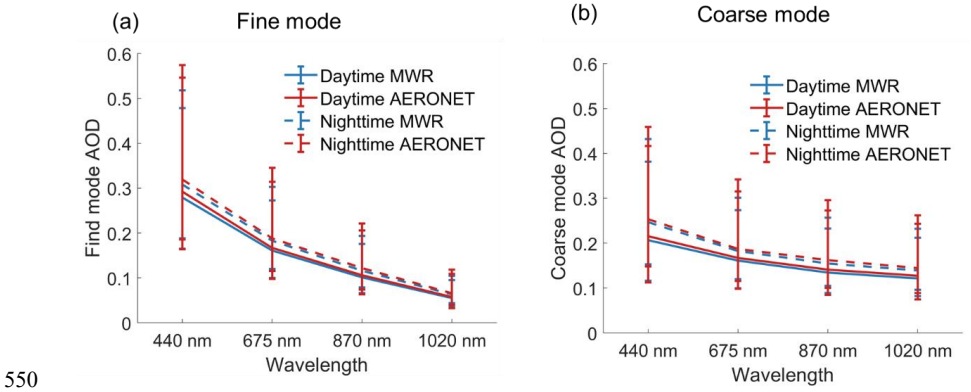

Figure 6. The relationship between wavelength and its corresponding AOD for MWR-based (blue lines) and the photometer (red lines) in the daytime (solid lines) and nighttime (dashed lines) for the (a) fine mode particles (440 nm to 870 nm Angstrom index > 1), and (b) coarse mode particles (440 nm to 870 nm Angstrom index < 1). The upper bound of the error bar is the 25th percentile, the middle is the median, and the lower bound is the 75th percentile.

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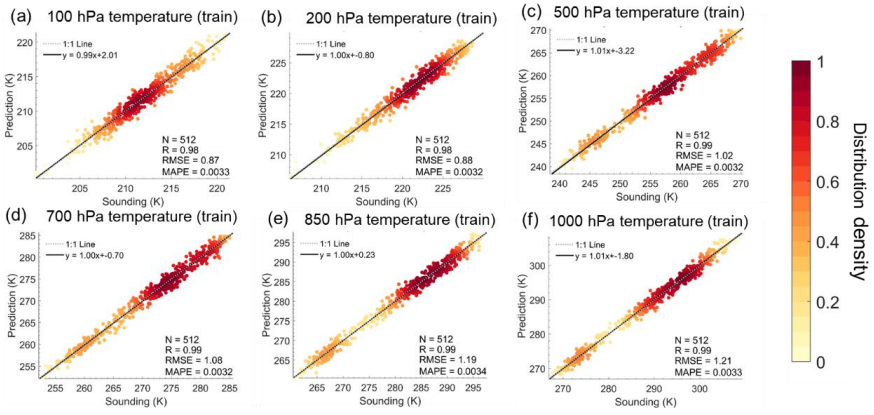

558

559 **Figure 7.** Density scatterplots of the vertical temperature profile in the train set of
560 MWR and sounding data at (a) 100 hPa, (b) 200 hPa, (c) 500 hPa, (d) 700 hPa, (e)
561 850 hPa, and (f) 1000 hPa. The dashed dark gray line represents the 1:1 line, and the
562 black solid line represents the linear regression line.

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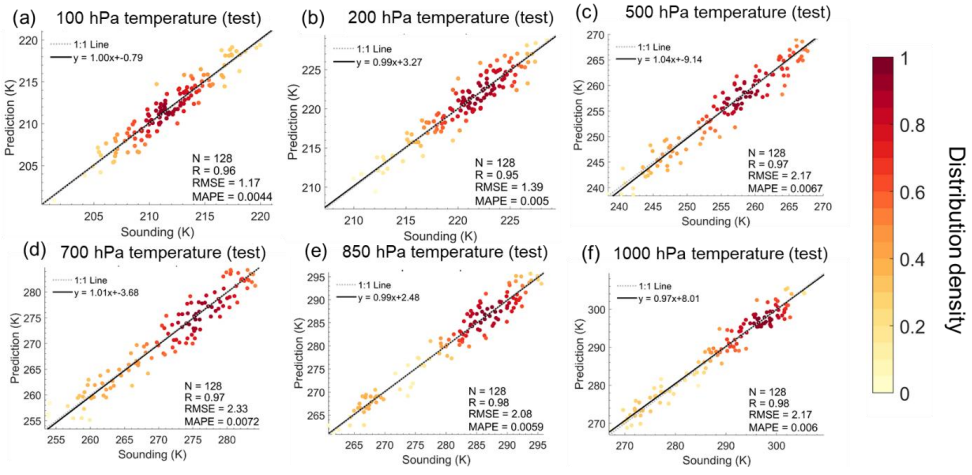

564

565 **Figure 8.** Density scatterplots of the vertical temperature profile in the test set of
566 MWR and sounding data at (a) 100 hPa, (b) 200 hPa, (c) 500 hPa, (d) 700 hPa, (e)
567 850 hPa, and (f) 1000 hPa. The dashed dark gray line represents the 1:1 line, and the
568 black solid line represents the linear regression line.

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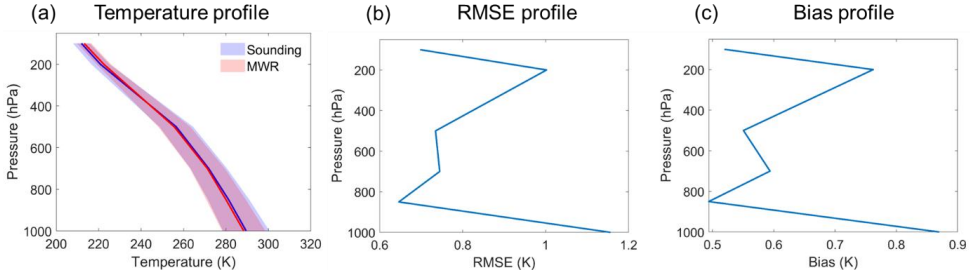

570

571 **Figure 9.** (a) Climatological mean vertical temperature profiles from sounding (the
572 blue shading and line) and MWR (the red shading and line). (b) RMSE vertical profile
573 calculated between sounding and MWR temperature, and (c) Similar to (b), but for the
574 bias vertical profile.

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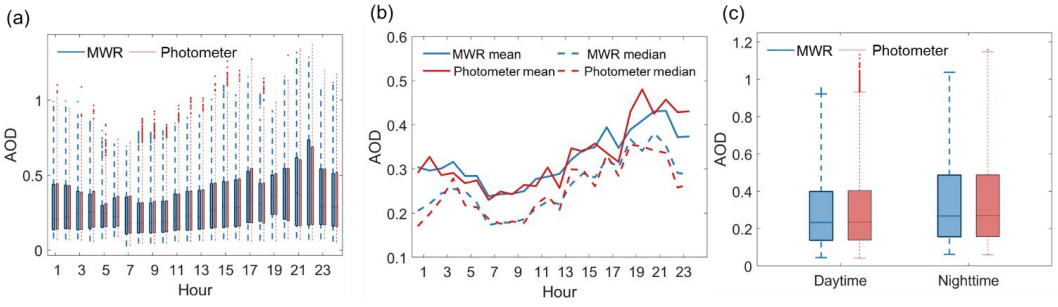

576

577 **Figure 10.** The diurnal cycle of MWR AOD and photometer AOD at 440nm. (a) The
578 boxplot of hourly MWR AOD (red boxplots) and photometer AOD (blue boxplots).
579 The small dots represent outliers greater than $q_{75} + 1.5(q_{75} - q_{25})$ or less than
580 $q_{25} - 1.5(q_{75} - q_{25})$, where q_{75} and q_{25} correspond to 75th and 25th percentile. (b)
581 The time series of mean AOD (solid lines) and median AOD (dashed lines) of MWR
582 AOD (red lines) and photometer AOD (blue lines). (c) The boxplot of daytime and
583 nighttime AOD. Blue boxes correspond to MWR data, and red boxes correspond to
584 photometer data.

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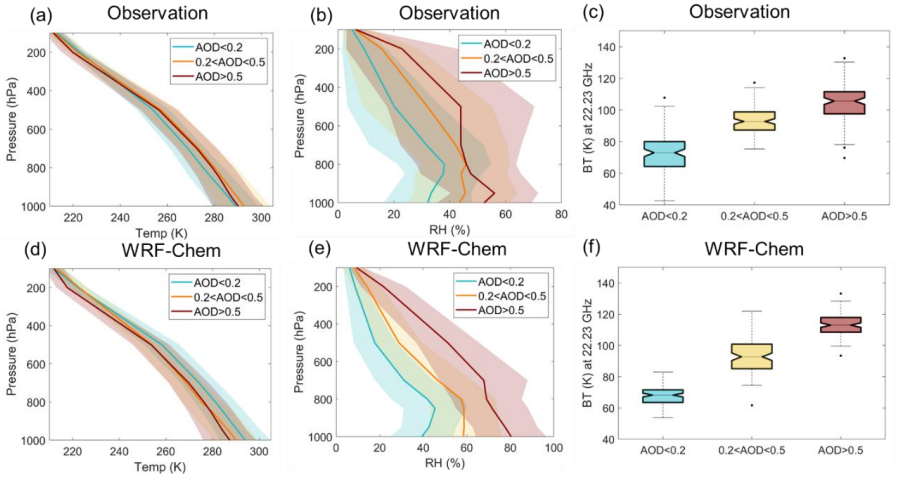

586

587 **Figure 11.** (a-b) The observational vertical profiles of temperature (Temp, unit: K)
588 and relative humidity (RH, unit: %) under various AOD levels. The cyan, orange, and
589 red solid lines correspond to low-level polluted scenarios (AOD<0.2), mid-level
590 polluted scenarios (0.2<AOD<0.5), and high-level polluted scenarios (AOD>0.5). (c)
591 Their corresponding brightness temperature (BT, unit: K) at 22.23 GHz calculated by
592 MonoRTM. (d-f) Similar to a-c, but for the WRF-Chem simulation. The shadings
593 represent the spread of samples with one standard deviation. All differences have
594 passed the significance test of p-value≤0.01 by Student's t-test.

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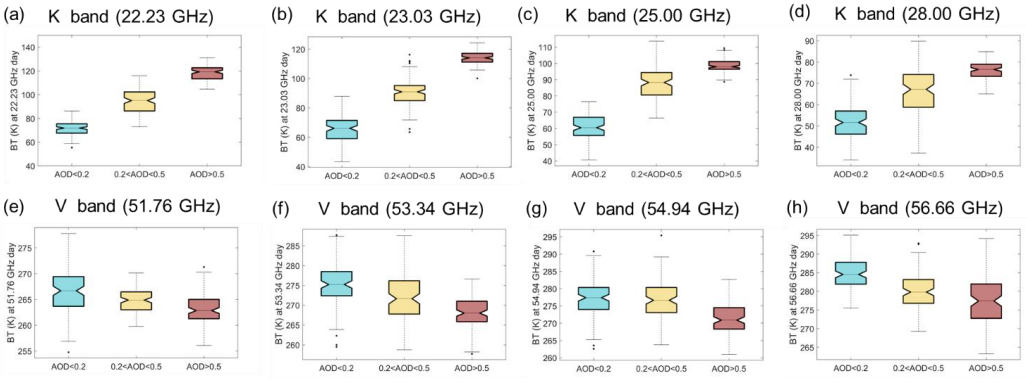

597

598 **Figure 12.** The boxplots of relationship between BT and AOD at 550 nm when fixing
599 the surface temperature at 270-275 K from 0000 UTC 18 December 2016 to 0000
600 UTC 20 December 2016 in the WRF-Chem simulation. The frequencies of BT are (a)
601 22.23 GHz, (b) 23.03 GHz, (c) 25.00 GHz, (d) 28.00 GHz, (e) 51.76 GHz, (f) 53.34
602 GHz, (g) 54.94 GHz, and (h) 56.66 GHz during the daytime.

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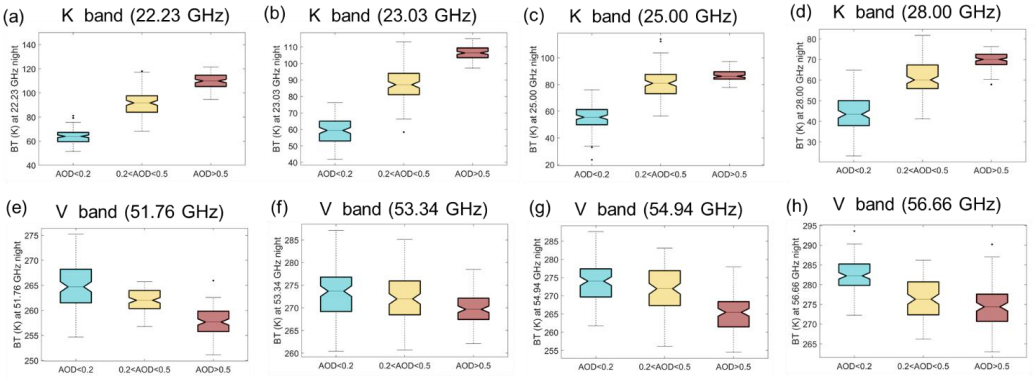

Figure 13. Similar to Figure 12, but for the nighttime.

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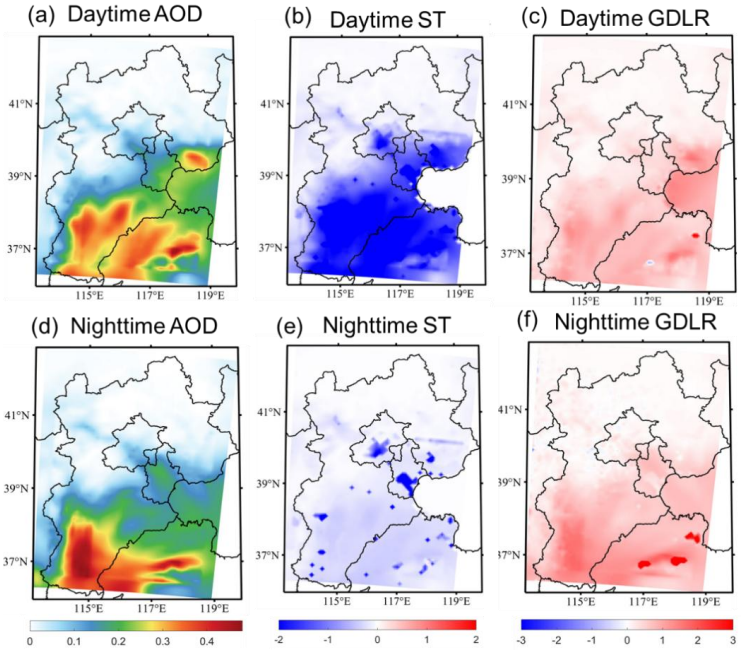

608

609 **Figure 14.** The difference of (a, d) aerosol optical depth (AOD), (b, e) surface
610 temperature (ST), and (c, f) ground downward longwave radiation (GDLR) between
611 EXP_AER and EXP_NOAER experiments (EXP_AER-EXP_NOAER) during the
612 (a-c) daytime and (d-f) nighttime. The daytime corresponds to the period from 2200
613 UTC 18 December 2016 to 1000 UTC 19 December 2016. The nighttime corresponds
614 to the period from 1000 UTC 19 December 2016 to 2200 UTC 19 December 2016.

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