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Evaluation of satellite aerosol retrievals with in situ aircraft and ground measurements: Contribution of relative humidity

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ABSTRACT

The contribution of relative humidity (RH) on Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol optical depth (AOD) was investigated based on in-situ aircraft and ground observations of aerosol and RH from 2007 to 2010 in Beijing, China. The profiles of dry aerosol particle number and size distributions with diameter ranging from 0.1 to 3.0 μm as well as RH were observed during aircraft measurement. The calculated AOD based on aircraft observed dry aerosol particles is lower than MODIS AOD under high RH, but consistent with MODIS AOD after accounting for the aerosol hygroscopic growth effect. A comparison of ground $PM_{2.5}$ and MODIS AOD further shows that the ratio of $PM_{2.5}$ concentration to AOD decreases with RH. These results collectively suggest that a strong aerosol hygroscopic growth effect on AOD. The averaged contribution of RH (hygroscopic growth) on AOD are estimated as 37% and 22% respectively based on in-situ aircraft and ground measurements, and hence aerosol concentration would be overestimated if the aerosol hygroscopic growth effect is neglected. As a result, it should be cautious with the applications of AOD in studying the complex relationships between aerosol and its climatic effects.

1. Introduction

Aerosol optical depth (AOD) is a fundamental aerosol property that can be retrieved from satellite data. With their wide spatial and spectral coverage, the observations by the MODIS instruments aboard the Terra and Aqua satellites provide an unprecedented opportunity to infer aerosol properties (Mishchenko et al., 2007; Streets et al., 2008; Zhao et al., 2008; Zhang and Reid, 2010; Xin et al., 2011, 2014; Ma et al., 2016; Kang et al., 2016; Gong et al., 2017). Satellite-derived AOD, as an indicator of aerosol particles, has been widely used to understand aerosol-cloud relations (Yuan et al., 2008; Koren et al., 2014; Zhao et al., 2018). Recently, satellite-derived AOD has also been used to derive surface $PM_{2.5}$ concentration, since the later variable is closely related to air quality (Chu et al., 2003;Wang and Christopher, 2003; Gupta and Christopher, 2008; Lv et al., 2017).

Relative humidity (RH) can significantly influence AOD since several aerosol components could hygroscopic grow in size at high RH due to water uptake, and hence change the aerosol optical properties, such as extinction, visibility. The variations in RH modify the micro-physical (e.g., shape and size modification), chemical compositions (e.g. heterogeneous chemical reactions) and optical properties of not only the hygroscopic aerosol mixtures but also mixtures containing some contribution of non-hygroscopic aerosols, e.g. organic carbon or black carbon (McFiggans et al., 2006). As a result, the aerosol mass extinction efficiency increases with RH (Bian et al., 2009), and AOD also increases with RH correspondingly since the AOD is determined by the product of aerosol dry mass and the mass extinction efficiency (Jeong and Li, 2010; Yoon and Kim, 2006). Hence, the contributions of RH in evaluation of satellite aerosol retrievals should be included, else the aerosol concentration would be overestimated.

In this study, a comprehensive measurement was carried out in Beijing to understand the contribution of RH (hygroscopic growth) on AOD. The profiles of dry aerosol particle number and size distributions ($RH \leq 40\%$) as well as RH were observed during aircraft measurement, together with ground $PM_{2.5}$ observations. The analysis focus on the following issues: (a) evaluate satellite aerosol retrievals with in-situ aircraft and ground measurements; (b) quantitatively estimate the contribution of RH on AOD.

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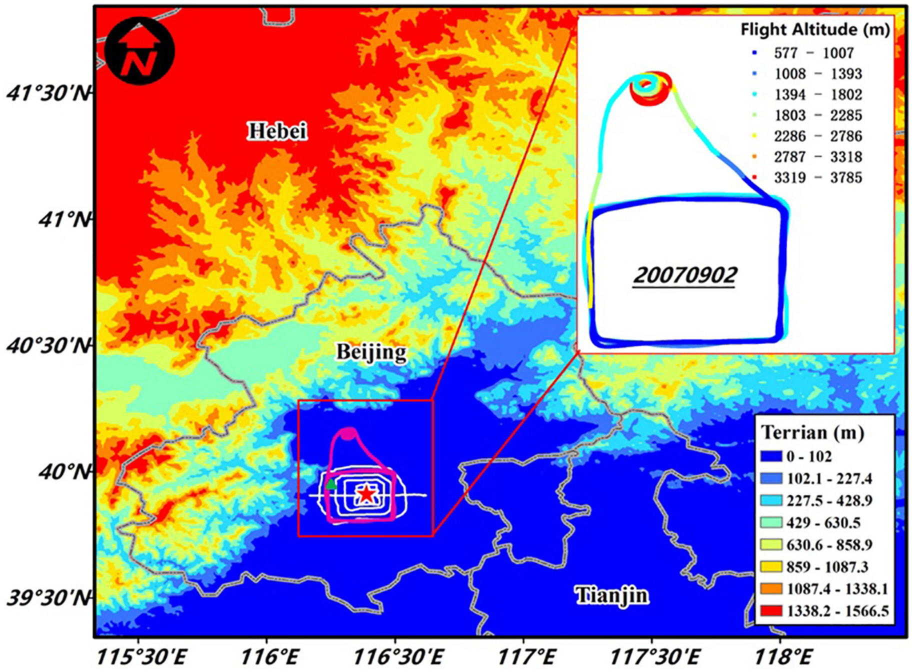

Fig. 1. Illustration of the typical flight pattern (Sep.2, 2007) during the aircraft campaign. The pentacle, triangle, and circle represent locations of the center of Beijing city, Baolian (BL) meteorological station, and Shahe airport, respectively. The white lines represent the 2nd to 5th rings surrounding the central Beijing and the central Chang'an street of Beijing city (straight line).

2. Description of the measurements

The comprehensive 3-year aircraft field campaign was conducted from Apr. 2007 to May. 2010, with an instrumented twin-engine Y-12 aircraft. A total of 156 flights was conducted during this campaign. The true airspeed of the aircraft is about 200 km h^{-1}; individual flights lasted about 3 h. A relatively fixed flight pattern was used, with quasi-circular, horizontal legs over the inner Beijing city (Fig. 1). After departing the Shahe airport, the aircraft climbed and flew over the Beijing inner city and spiraled down around the rectangle of the 4th ring from 2100 m to 600 m with an vertical interval of 300 m. During each flight, approximately 3–6 horizontal rectangular legs of about 70 km circumference and required about 30 min of every circle. After finishing this quasi-circular flight pattern over the inner city, the aircraft spiraled down to the Shahe airport and then conducted measurements of vertical profiles up to about 3600 m above ground before landing. The circle diameter was about 10 km in these profiling flights and took approximately 30 min. Aerosol properties, gas pollutants, and meteorological parameters were measured. Aerosol particles were measured by a passive cavity aerosol spectrometer probe (PCASP-200, DMT Inc.), with the particle size ranging from 0.1 to 3.0 μm in diameter. Three heaters in PCASP were turned on during the measurement, which can reduce the RH to 40% in the inlet air (Strapp et al., 1992). The meteorological measurements included location, temperature, relative humidity, barometric pressure and wind using an aircraft integrated meteorological measurement system (AIMMS-20, Advantech Research Inc.). The PCASP-200 and AIMMS-20 instruments were mounted under the wing of the aircraft. The details about the instruments and data processing are also described in Chen et al. (2013) and Quan et al. (2017). The temporal resolution of PCASP data and meteorological variables was 1 Hz. Their vertical profiles were calculated with a vertical interval of 50 m.

The ground observations were carried out at Baolian (BL) meteorological station, Chinese Meteorological Administration (CMA) (39 °56′N, 116 °17′E), which is located between the west 3rd and 4th highways in Beijing. The mass concentration of $PM_{2.5}$ was observed by an R&P model 1400a Tapered Element Oscillating Microbalance (TEOM, Thermo Scientific Co., USA) instrument, with a 2.5 μm cyclone inlet and an inlet humidity control system. This instrument was installed in an air-conditioned room and was operated with a hydrophobic filter material to reduce the humidity of the incoming sampled air (see also Zhao et al., 2009; Quan et al., 2014). Meteorology variables were observed by WXT-510 (Vaisala Co., Finland). The $PM_{2.5}$ and RH used in this work are daily average.

The MODIS data used in this paper were the Collection 6 aerosol product (with a 10 km × 10 km resolution). According to the NASA research groups' suggestion (Ichoku et al., 2002), data matching was done in the following manner: if at least five pixels fell within a 50 km × 50 km box centered on a sunphotometer site, the mean satellite-retrieved AOD was calculated. Observed AOD with standard deviation (SD) > 0.5 was excluded to reduce validation errors. As a result, a total of 638 days MODIS data were selected from 2007 to 2010 with the procedure above.

The measured vertical profiles of dry aerosol particle number and size distributions were used together with Mie theory to derive AOD. The PCASP instrument uses a preset refractive index value $m = 1.585 + 0i$ to calculate the particle size (Strapp et al., 1992). This value was also used in the Mie scattering calculations in this work for self-consistency. The aircraft AOD (calculated based on aircraft measurement) and the MODIS AOD need to be co-located both spatially and temporally for inter-comparison. To compare with MODIS AOD, only flight data obtained within the same location as MODIS data and at the same time within ± 2 h from the time of MODIS data are used in analysis. Besides, the flights in cloudy weather were alsoexcluded. As a result, a total of 29 flights during the campaign were selected according to above criteria.

3. Results and discussion

3.1. Comparison of aircraft AOD with MODIS AOD

The typical maximum altitude of aircraft measurement is 3600 m in this work. So the aircraft AOD is only partial AOD within the layer aircraft measured, while the MODIS AOD is the AOD of the entire column/atmosphere. Therefore, the aircraft AOD should always be lower than the MODIS AOD in theory. In fact, aerosol concentrations usually decrease exponentially with altitude (Zhang et al., 2009; Liu et al., 2009), and large fraction of aerosol particles locate in low layer.

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