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다분광랭리 기법에 기반한 지상원격탐사장비 직달광 관측을 활용한 수증기 전량 산출

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Water vapor retrievals from the ground-based direct-Sun measurements based on the spectral Langley method

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요약: 대기 중에 존재하는 수증기는 대부분 바닷물의 증발로 인해 대기로 유입되며, 수문순환에 있어 중요한 인자 중의 하나이다. 본 연구에서는 아시아 국제 공동 대기질 캠페인(Airborne and Satellite Investigation of Asian Air Quality; ASIA-AQ)기간 동안 스마트에스(Spectral Measurements for Atmospheric Radiative Transfer-spectroradiometers) 장비와 에어로넷(AERONET) 장비를 설치하여 2023년 12월부터 2024년 2월까지 운영하였다. 새롭게 개발된 전층 수증기량 산출 알고리즘은 다분광랭리 기법에 기반하여 직달광 관측데이터를 사용하며, 에어로넷 데이터와 비교에서 매우 우수한 일관성을 보였다(상관관계: 0.99, 기울기: 1.03, 절편: -0.04). 본 연구의 수증기 전량 알고리즘이 국제 지상원격관측 네트워크에 적용된다면, 미량기체(예, H_2O, NO_2, $HCHO$, SO_2, O_3), 에어로졸, 구름 간의 상호작용을 이해하고 이들이 기후 및 수문순환 시스템에 미치는 영향을 분석하는 데 중요한 정보를 제공할 수 있을 것으로 기대된다.

주요어: 전층 수증기량, 다분광랭리 기법, 직달광, 스마트에스, 에어로넷

ABSTRACT: Water vapor is one of the most important species in the hydrological cycle, mainly emitted from ocean evaporation. In this study, we deployed the Spectral Measurements for Atmospheric Radiative Transfer-spectroradiometer (SMART-s) and AErosol RObotic NETwork (AERONET) instruments at Suwon, South Korea, during the Airborne and Satellite Investigation of Asian Air Quality (ASIA-AQ) campaign from December 2023 to February 2024. The newly developed SMART-s total precipitable water (TPW) retrieval algorithm utilizes direct-Sun measurements based on the spectral Langley calibration method. The SMART-s retrievals of the TPW showed excellent agreement with the collocated AERONET products (correlation coefficient of 0.99, slope of 1.03, and offset of -0.04). The TPW measurements from globally networked SMART-s or Pandora instruments can provide valuable information for analyzing interactions between trace gases (e.g., H_2O, NO_2, $HCHO$, SO_2, O_3), aerosols, and clouds, thereby contributing to understanding its role in the climate and hydrological systems.

Key words: total precipitable water, spectral langley method, direct-sun measurement, SMART-s, AERONET

1. Introduction

Water vapor is the crucial gas of the atmosphere's hydrological cycle (IPCC, 2013), mainly emitted from ocean evaporation. It affects the water cycle in drylands through absorption by soil (Lopez-Canfin *et al*., 2022) and impacts the global radiation budget by absorbing infrared light, thereby acting as a natural greenhouse gas (Trenberth *et al*., 2007). Through water evaporation and condensation, water vapor provides the energy to drive moist convection and subsequent precipitation and determines the potential stability of the atmospheric columns (Fragkos *et al*., 2019). In particular, condensation of water vapor in the lower troposphere induces latent heat and affects the vertical structure of the tropospheric diabatic heating (Trenberth and Stepaniak, 2003). To accurately predict and analyze the climate, it is essential to have a precise understanding and estimation of water vapor. Water vapor measurements are also useful for analyzing the hygroscopic growth of atmospheric particles, thus affecting aerosol optical properties (e.g., Jeong *et al*., 2018, 2022).

Total precipitable water vapor (TPW) represents the amount of atmospheric water vapor contained in a vertical column of a unit cross-section and can be accurately measured by ground-based sun-tracking instruments based on Beer's Law. Radiosonde measurements have been used to measure TPW for a long time. However, this measurement has limitations (e.g., freezing of moisture sensors, the release of latent heat, and phase lag can lead the errors in the estimation of moisture) (Campmany *et al*., 2010). To consider these limitations and the spatial-temporal coverage, several measurements have been developed, including satellite and ground-based measurements, and complement the TPW from radiosonde (e.g., Halthore *et al*., 1997; Holben *et al*., 1998; Dostalek and Schmit, 2001; Mears *et al*., 2015). In particular, the Aerosol Robotic Network (AERONET), a global network of Cimel sun photometer, retrieves the TPW by measuring the water vapor absorption band around 940 nm (Holben *et al*., 1998), and Several studies extensively have evaluated the AERONET TPW products using microwave radiometry, GPS, and radiosondes data (Sapucci *et al*., 2007; Campmany *et al*., 2010; Pérez-Ramírez *et al*., 2014). POM instruments deployed for the SKY radiometer NETwork (SKYNET) also measure direct solar irradiance from the ground and provide TPW retrievals with aerosol products (Campanelli *et al*., 2014).

Recently expanding ground-based hyperspectral remote sensing instruments such as the Pandora and Spectral Measurements for Atmospheric Radiative Transfer-spectroradiometer (SMART-s) also retrieve trace gases, including ozone (O_3), nitrogen dioxide (NO_2), and formaldehyde (HCHO) in addition to the aerosol and TPW. This study aims to develop a retrieval algorithm of the TPW using the SMART-s measurements based on the spectral Langley calibration method (Jeong *et al*., 2018) to analyze trace gas-aerosol-cloud interactions. To check consistency, we also compared the retrieved water vapor amount with the collocated AERONET measurements in this study.

2. Method

2.1. Measurements

Pandora network group at NASA (National Aeronautics and Space Administration) / GSFC (Goddard Space Flight Center) initially developed the SMART-s instrument (Jeong *et al*., 2018), and the SMART-s shares most parts of the standard Pandora instrument except for the spectrometer. The same manufacturer (i.e., Avantes; https://www.avantes.com/) built the SMART-s, and the Pandora spectrometer, but the SMART-s covers a wider spectral range (i.e., 280-820 nm) with a lower spectral resolution (~1.0 nm Full-width-half-maximum with about ×3.7 oversampling). Detailed information on the SMART-s instrument is summarized in Jeong *et al*. (2022). We deployed the SMART-s at Suwon, South Korea (37.26°N latitude, 126.99°E longitude), which is a downwind area of the Seoul-Metropolitan area during the Airborne and Satellite Investigation of Asian Air Quality (ASIA-AQ) campaign from 1 December 2023 to 15 February 2024 (see Figure 1). One AERONET instrument was also deployed during this period, and we used the AERONET TPW data (Version 3.0, Level 2.0) to check retrieval consistency in this study.

2.2. Spectral Langley calibration method

The SMART-s algorithm aims to derive information on aerosols and trace gases simultaneously and consists of several retrieval steps from fundamental quantities (i.e., aerosol optical depth and total column amounts of trace gases) to higher-order inversion products (e.g., aerosol
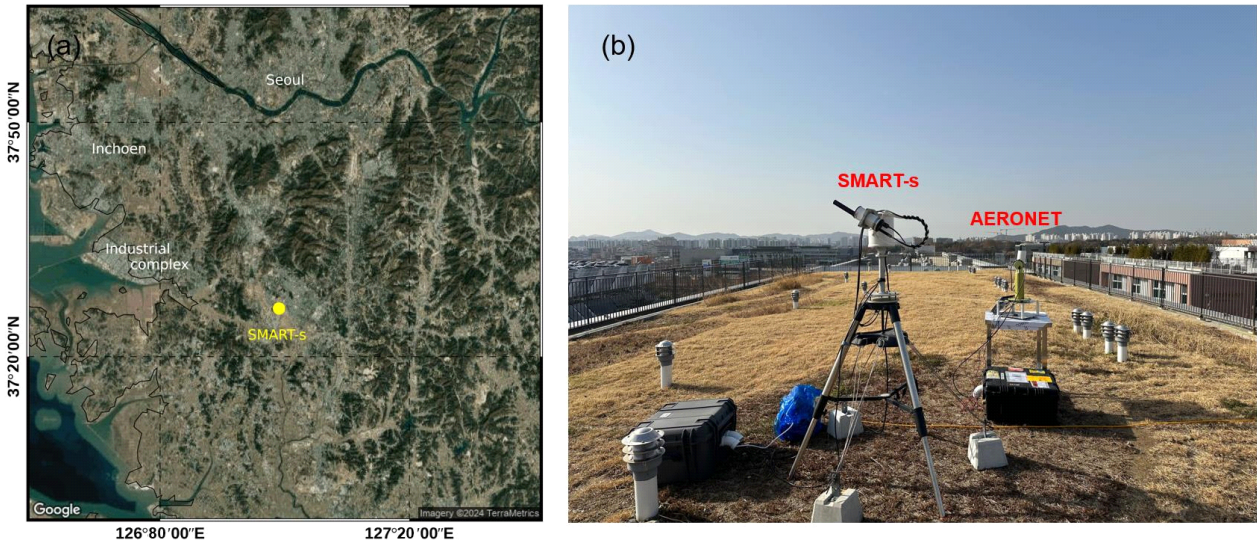
Fig. 1. (a) Measurement location of the SMART-s instrument marked with yellow circle. (b) Picture of SMART-s and AERONET instruments deployed in Suwon.

optical properties, vertical profiles of atmospheric species) using both the direct-sun and diffuse sky radiances (Jeong *et al*., 2018, 2020). The spectral Langley calibration method provides total column amounts of aerosols and trace gases based on the Langley method (Jeong *et al*., 2018, 2022), and Jeong *et al*. (2018) retrieved spectral aerosol optical depth which showed excellent consistency with the collocated AERONET measurements (Jeong *et al*., 2018). The SMART-s TPW retrieval algorithm developed in this study utilizes water vapor absorption bands from 550 to 680 nm, whereas the aerosol algorithm uses from 330 to 800 nm. Another difference is that we used the HITRAN (high-resolution transmission molecular absorption database; https://hitran.org/) 2020 water vapor absorption cross-section (Rothman *et al*., 2013), whereas the aerosol algorithm adopts the Langley optical thickness (Jeong *et al*., 2018).

3. Results

Figure 2a shows an example of the spectral optical thickness fitting result based on the SMART-s algorithm from 550 to 680 nm, where weak water vapor absorption bands are distributed. This sample was measured on 6 January 2024 at 03:37 UTC when the aerosol optical thickness was low. Figure 2b shows the spectral bias of the fitted spectrum from the measured optical thickness, which ranged about ±0.1 at around 380 and 630 nm.
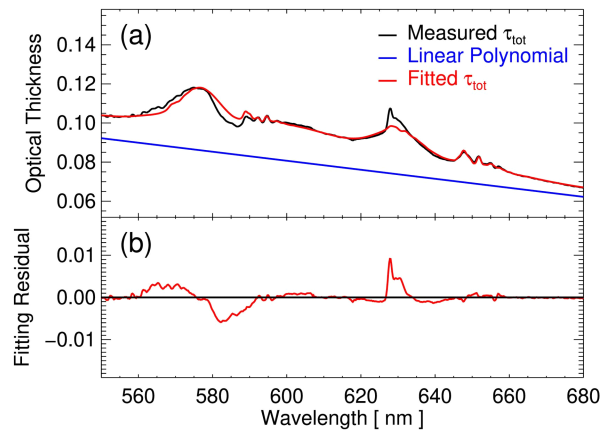

Fig. 2. (a) An example of spectral fitting of optical depth in the water vapor absorption band from 550 to 680 nm on 6 January 2024 at 03:37 UTC at Suwon, South Korea. Panel (b) indicates the residual between measured optical thickness and fitting parameters.

These biases are attributable to uncertainties in the calibrated slit function of the instrument and HITRAN database and various broadening processes the SMART-s algorithm does not account for yet. Jeong *et al*. (2018) adopted 4~5 polynomials for the spectral fitting of the aerosol optical thickness from 330 to 800 nm. In contrast, we adopted two low-order polynomials (i.e., zero and first order) as the fitting window of the TPW spectral fitting is narrower than that of the aerosol algorithm (i.e., 550-680 nm). Note that the low-order polynomials in Figure 2a (blue line) represent aerosol and cloud optical thickness
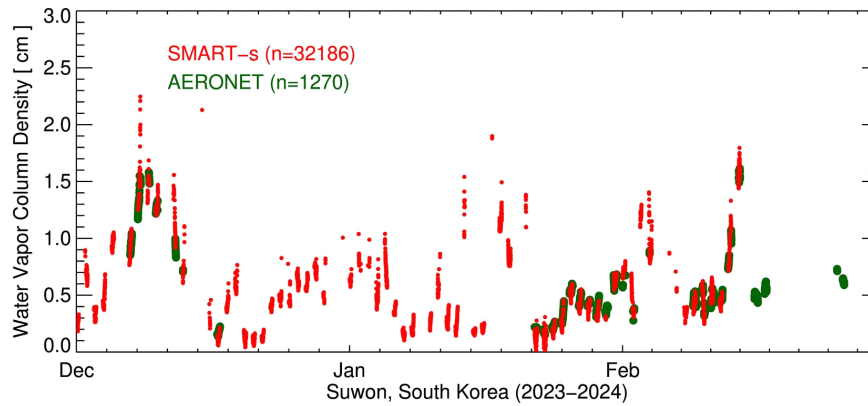
Fig. 3. Temporal variation of total precipitable water vapor in Suwon, South Korea, from 1 December 2023 to 28 February 2024.

(ACT), which is also useful information for analyzing the water vapor interactions with aerosols and clouds (e.g., Jeong *et al.*, 2018, 2022).

Figure 3 shows temporal variations of the TPW in Suwon retrieved from the AERONET (green) and SMART-s (red) during the measurement period. The AERONET instrument stopped measurements from 16 December 2023 to 22 January 2024 due to connection issues, and the SMART-s stopped operation on 15 February 2024. Wintertime in South Korea is typically dry, and the retrieved TPW data ranges up to 2 cm, as shown in Figure 3. During the measurement period, TPW retrievals from the SMART-s showed excellent consistency with the AERONET products. During the analysis period, 32,186 and 1,270 samples are collected by the SMART-s and AERONET, respectively.

Figure 4 compares retrieved TPW from the SMART-s with the collocated AERONET products during the measurement period. It shows excellent consistency with a correlation coefficient of 0.99 and a mean bias error (MBE) of -0.023. The dotted line depicts a one-to-one line, and the solid line indicates the regression line, which is close together (slope of 1.03 and offset of -0.04). The color of the circles represents the ACT. Relatively higher discrepancies appeared when the ACT is high, as shown in Figure 4. The direct-Sun algorithm assumes all the photons recorded are direct solar irradiance, which is valid when the optical thickness of the atmosphere is low. However, for the thick cloud cases (e.g., ACT > 4.0), measured direct-Sun data could be contaminated by the diffuse sky radiances within the field-of-view (FOV) of the collimator (i.e., ~2.2°). During the quality assurance processes of the SMART-s algorithm, retrievals with opti-
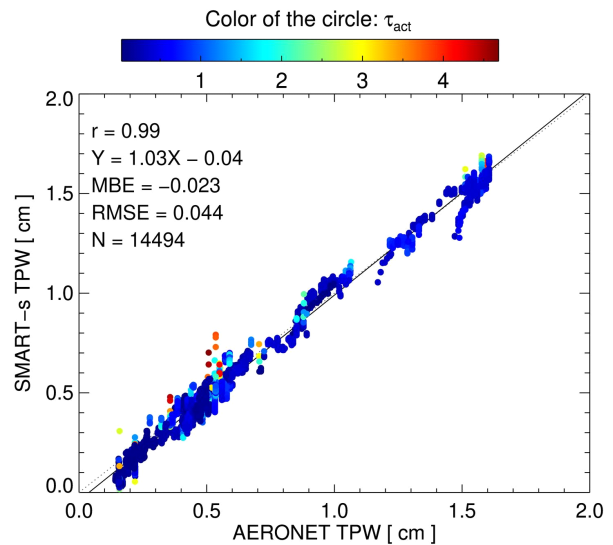

Fig. 4. Comparison of the total precipitable water (TPW) retrievals from the SMART-s with those from the AERONET (Version 3, Level 2.0) data in Suwon, South Korea from 1 December 2023 to 15 January 2024. The color of the circles depicts cloud and aerosol optical thickness (ACT) at 550 nm.

cal depths greater than 3.0 and air mass factors higher than 4.0 are screened. In general, the SMART-s direct-Sun TPW retrievals showed good agreement with the benchmark AERONET data.

4. Summary and Discussions

The SMART-s and AERONET were deployed at Suwon, South Korea, during the ASIA-AQ campaign from December 2023 to February 2024. We retrieved the total precipitable water from the SMART-s direct-Sun measurement based on the spectral Langley calibration method in this study. Retrieved TPW from the SMART-s showed excellent

agreement with the benchmark AERONET products (correlation coefficient of 0.99, slope of 1.03, and offset of -0.04). In the future, the TPW retrievals, in addition to the previously developed products (e.g., aerosol, cloud, NO_2, O_3, HCHO) from globally networked instruments, can provide valuable information for analyzing their interactions and impacts on meteorology and climate systems. It also can be used to validate various satellite-based TPW inversion products.

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