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Evaluation of maritime aerosol optical depth and precipitable water vapor content from the Microtops II Sun photometer

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ABSTRACT

Aerosols and precipitable water vapor over oceans represent the main components of the land-atmosphere-ocean ecosystem and play an important role in the exchange of substances and the radiative balance on the global scale. Using AERONET level 2.0 data from islands and coastal sites as reference data, this study evaluated the validity of maritime aerosol optical depth (AOD) in each band and precipitable water vapor (PWV) content retrieved from Microtops II Sun photometer measurements based on ship-borne data collections. The results showed that the bias of the AOD at each wavelength from Microtops II was in the range of −0.043 to −0.005, which could be caused by improper pointing at the sun, dirty optics or unstable elctronics. The root mean square error (RMSE) was in the range of 0.035–0.093, and the mean absolute percentage error (MAPE) varied from 15.88% to 34.42%, which were attributed to the comprehensive effect of both random and systematic errors during the measurements. The average Ångström exponent was 1.402 and the bias, RMSE, and MAPE were −0.081, 0.249, and 14.06% respectively, and the error of Ångström exponent was mainly derived from the cumulative one from the AOD at each wavelength. The average PWV content over oceans was 2.740 cm and the bias, RMSE, and MAPE were −0.071, 0.268 cm, and 8.58% respectively; this indicated that the retrieved PWV had a good accuracy.

1. Introduction

Aerosols and precipitable water vapor (PWV) over the oceans represent important components in the atmosphere and they also produce clouds and precipitation, which play a key role in weather and climate changes [1,2]. In addition, as the main components in the land-atmosphere-ocean ecosystem, aerosols and PWV affect the radiative balance directly and indirectly on a global scale [3,4] and further have an impact on changes in the environment and the climate [5]. Therefore, they are essential factors in meteorological and climatological studies. Moreover, aerosol scattering and PWV absorption for solar radiation affect the quality of bio-optical products of satellite ocean color sensors to a large degree [6] and maritime aerosol optical depth (AOD) and PWV content are necessary parameters used in atmospheric correction algorithms for ocean color remote sensing [7]. The AOD and its Ångström exponent α are also very important optical parameters for indicating aerosol properties, and the Ångström exponent can be calculated from AOD, which is commonly used as an indicator of aerosol size, since the AOD spectral shape of the extinction is related to the particle size [8]. Hence, the measurements of maritime AOD and PWV content improve our understanding of the atmospheric properties over the oceans.

At present, ground- and space-based observations are two main methods for determining AOD and PWV content. In ground-based

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observations, sun photometers [9] and lidar [10,11] can measure the AOD and PWV content simultaneously while radiosonde [12] and ground-GNSS [13] data can provide the PWV content. Space-based satellite sensors can capture the radiance of the earth's surface and the AOD and PWV content can be retrieved by sensors such as MODIS [14], SeaWiFS [15], NOAA/AVHRR [16], and FY3/MERSI [17]. The two observational methods have different but complementary characteristics. Ground-based observations can acquire high-frequency data in one day but only for discrete locations. In contrast, satellite-based sensors can cover more extensive areas of the earth once or twice per day and the observing frequency is relatively low [5]. The two observation methods meet different requirements for field campaigns and ground-based measurements also provide calibration and validation data for satellite remote sensing.

For ground observations, the Microtops II Sun photometer, commercially manufactured by the Solar Light Company, USA, is a five-channel, portable and low-cost instrument that is easy to operate [18]. It is designed for the measurements of AOD and PWV content. It has been used quite widely in field campaigns and experiments onboard ship platforms [19–21]. For more than a decade, the NASA SIMBIOS project has collected, processed, and archived large amounts of maritime AOD and PWV data, which are shared in the Maritime Aerosol Network (MAN) [6,21,22]. However, there are relatively few evaluations of the data quality of maritime AOD and PWV measured by the Microtops II Sun photometer. Since the AERONET (AErosol RObotic NETwork) master-CIMEL sun photometer CE-318 is commonly used as a reference to calibrate the Microtops II by the NASA Goddard Space Flight Center (GSFC) instruments [5,19–22], and the absolute error for AOD is 0.01–0.02 and the uncertainty of PWV is 12% retrieval with the CIMEL sun photometer CE-318 when all the measurements sequence and data processing are carried out within AERONET protocols [9], the measurements of sun photometer CE-318 in the AERONET are widely used as the reference to validate the data for satellite remote sensing. For example, Roman et al. (2014) compared the water vapor column product retrieved from the MODIS, aerosol optical depth at 443 nm and 675 nm retrieved from the MISR and the Angstrom exponent with the ground-based sun photometer CE-318 measurements at six AERONET stations [23]. Li et al. [23] validated the PWV retrieved from a multifilter rotating shadowband radiometer (MFRSR) with the AERONET PWV data over the semi-arid area of northwest China, which showed show a good agreement between MFRSR and AERONET PWV with relative bias of 2.9% and RMS difference of 9.1% [24]. Ralph et al. (2005) assessed quantitatively the AOD over land and ocean from the Multiangle Imaging Spectroradiometer (MISR) by comparison with a 2-year measurement record of globally distributed AERONET Sun photometers [25]. Torres et al. validated TOMS retrievals of aerosol optical depth over continents by comparison with AERONET ground-based observations, which showed to agree reasonably well [26]. Hence, in this study, we also used AERONET level 2.0 data from island and coastal sites as reference data to validate the maritime AOD and PWV measurements acquired by the Microtops II Sun photometer.

2. Data and methods

2.1. MAN Microtops II Sun Photometer data

The Microtops II Sun photometer is the standard instrument used for measurements shared in the MAN and is designed to measure AOD at 8 optional standard wavelengths from 340 nm to 1020 nm and the PWV content at 936 nm. The Microtops instruments currently have five channels with two configurations in the MAN: 340, 440, 675, 870, and 936 nm or 440, 500, 675, 870, and 936 nm. MAN has collected a large amount of Microtops II Sun photometer measurements from more than 400 ocean cruises since November 2006. The measurement areas have covered various parts of the Atlantic Ocean, the Northern and Southern Pacific Ocean, the South Indian Ocean, the Southern Ocean, the Arctic Ocean, and inland seas [27]. The MAN Microtops II data include maritime AOD measurements at each wavelength, the Ångström exponent α calculated based on the AOD from 440 nm to 870 nm using a least squares method, the PWV content, and AOD measurements at 500 nm partitioned into fine and coarse components. All data have three quality levels: Level 1.0 (unscreened), Level 1.5 (cloud-screened), and Level 2.0 (cloud-screened and quality assured) [27]. This study selected MAN Microtops II level 2.0 data from November 2006 to December 2016 to evaluate the validity. The data were downloaded from the MAN website at https://aeronet.gsfc.nasa.gov/new_web/maritime_aerosol_network.html.

2.2. AERONET sun photometer CE318 data

The AERONET program is a group of ground-based remote sensing aerosol networks established by NASA and PHOTONS (Holben et al. [9]) that operates a database of long-term, continuous, and readily accessible public domain data of AOD and PWV data. The Sun photometer CE318 (made by the French company CIMEL Electronique) is the standard instrument in the AERONET and is used to monitor aerosol optical parameters and PWV every 15 min using 8 channels in the wavelengths of 340 nm, 380 nm, 440 nm, 500 nm, 675 nm, 870 nm, 936 nm, and 1020 nm. The CE318 is not only able to observe direct sunlight but also can measure the scattered atmospheric light using a combination of an ahnucantar (horizontal) scan and a principal plane (vertical) scan at several wavelengths and the polarization of diffused light by the principal plane at a wavelength of 870 nm [28]. According to the Beer-Lambert-Bouguer law, the direct solar radiation in each channel can be used for the retrieval of AOD and that at 936 nm is used to retrieve the PWV content. Because the level 2.0 data of AERONET automatically implements a cloud-screening algorithm and quality control, the uncertainties of the AERONET data are 0.02 and 0.01 for the AOD at 440 nm and 675 nm respectively and 12% for the PWV content [8]. At present, more than 900 CE318 sun photometers have been included in the AERONET and are deployed worldwide on land and in coastal and island areas. There are 53 sites (Fig. 1) that are matched with the geographical coordinates of the Microtops II Sun photometer measurements along the cruise tracks. The AERONET Level 2.0 data at these sites are regarded as reference data to evaluate the validity of the Microtops II Sun photometer measurements. These data are available on the AERONET website at http://