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Evaluation of the AVHRR DeepBlue aerosol optical depth dataset over mainland China

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ABSTRACT

Advanced Very High Resolution Radiometer (AVHRR) on-board NOAA series satellites have been used to observe the Earth's surface and clouds for almost 40 years. Limited by bands and problematic instrument calibration, aerosol studies using AVHRR data have focused on retrieving data over the ocean. However, continuous developments have made it possible to retrieve aerosol over land as well. The newly developed AVHRR Deep Blue (DB) technique has been applied to process global aerosol datasets over both land and the ocean during 1989–1990, 1995–1999 and 2006–2011. This paper aims to evaluate, in detail, the performance of the AVHRR DB aerosol optical depth (AOD) dataset over mainland China by comparison with both ground-based data and satellite aerosol products. The ground-based validation results show that DB AOD is close to ground-based AOD when AOD is moderate during winter, while DB underestimates AOD when AOD increases over 1.0 during summer over vegetated surfaces. AVHRR DB underestimates dry, urban and transitional surfaces in Western China due to the high uncertainty in low retrievals over bright surfaces. Cross-comparison with the Moderate-resolution imaging spectrometer (MODIS) DB aerosol dataset shows that the disadvantages of the single longer visible channel are greatly increased over bright surfaces. Together with problematic instrument calibration, the differences between the two datasets over most of mainland China are significant. Meanwhile, the differences show strong seasonal variation characteristics.

1. Introduction

Atmospheric aerosol is colloid of solid or liquid suspended in the atmosphere. As part of the atmosphere, it not only scatters solar radiance but also influences the cloud formation as a cloud condensation nucleus and interacts with the Earth's energy budget (Andreae and Rosenfeld, 2008; Tzanis and Varotsos, 2008). As the IPCC (2013) reports, calculating aerosol's effects on the Earth energy system remains considerably uncertain, and understanding of the mechanisms of its interactions with the rest of the Earth system are needed (Varotsos, 2005; Varotsos et al., 2012). The traditional and well-accepted aerosol research is from ground-based observations, such as the aerosol column optical depth (AOD) measured by CE-318 instruments (Holben et al., 1998; Che et al., 2009). However, traditional ground-based aerosol studies are limited by the sparse spatial distribution of ground-based sites. Satellites from the space can observe the Earth or the atmosphere continuously with great detail and have the potential to make up for the limitations of traditional ground-based measurements (Griggs, 1979; Kaufman et al., 1997a, 1997b; Diner et al., 2005; Hsu et al., 2013).

Quantitative aerosol remote sensing has increased in popularity since the 1990s. Many instruments on board different satellite platforms have been applied to aerosol retrieval. The most well-known and accepted aerosol products are provided by Moderate-resolution imaging spectrometer (MODIS) instruments, including Dark-Target (DT) (Levy et al., 2013), Deep Blue (DB) (Hsu et al., 2013) and MAIAC (Lyapustin et al., 2011b). Satellite instruments with dual or multi-views have advantages in observing quantitative aerosol, such as the Advanced Along-Track Scanning Radiometer (AATSR) and the Multiangle Imaging SpectroRadiometer (MISR). AATSRs on board ENVISAT satellites have been used to retrieve aerosol properties; in particular, the European Space Agency (ESA) aerosol-CCI initiative registers three aerosol products from (A)ASTR, including the (A)ASTR dual-view aerosol

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retrieval algorithm (ADV) (Kolmonen et al., 2016), Oxford-RAL Retrieval of Aerosol and Cloud algorithm (ORAC) (Thomas et al. 2009) and Swansea algorithm (SU) (Bevan et al., 2012). Additionally, instruments can observe aerosol from polarization information, for example, POLarization and Directionality of the Earth's Reflectance (POLDER) provides polarization information and has been used to retrieve aerosol over land (Herman et al., 1997) and ocean (Vachon et al., 2004).

The Advanced Very High Resolution Radiometers (AVHRR) onboard NOAA series satellites are the only operational sensors that have observed the Earth's surface and cloud formations continuously for almost 40 years (since 1978). The primary purpose of AVHRR is to detect global vegetation such as long time series NDVI (Anyamba and Tucker, 2005, Tachiiri 2005), global crop yield dataset (Zhang and Zhang, 2016), regional primary productivity (Ricotta et al., 1999), land use and land cover (Chen et al., 1999; He et al., 2017), cloud formations and temperature of the Earth's surface remotely. Such long-time coverage helps to successfully expand applications of AVHRR to aerosol property retrieval over both land and ocean (Hauser et al., 2005; Riffler et al., 2010; Li et al., 2013; Xue et al., 2017; Hsu et al., 2017). However, most of aerosol retrieval works focus on areas over oceans (Rao et al., 1989; Stowe et al., 1997; Ignatov and Stowe, 2002; Ignatov et al., 2004) because of the oceanic surface's favourable characteristics, such as low reflectance without much variation. On the contrary, aerosol retrieval over land is more difficult because the reflection is complex and inhomogeneous, so building the bidirectional reflectance distribution function (BRDF) is more difficult. Together with the relative high reflectance, separation of the aerosol contribution from top-of-atmosphere (TOA) reflectance is more difficult. Usually, the multi-bands or multi-views method can solve this problem (Kaufman et al., 1997a; Kahn et al., 2005; Thomas et al., 2009; Li et al., 2013). Otherwise, AVHRR only has two visible channels at 630 and 850 nm from one observation view, causing more difficulty in separating the aerosol contribution from TOA reflectance and further aerosol retrieval. Additionally, severe problems exist with the calibration of AVHRR since it lacks an on-board calibration system, which leads to inapplicability of the pre-launched calibration coefficient with irresistible instrument aging (Dinguirard and Slater, 1999; Gorroño et al., 2017). Additionally, orbits of NOAA-15 and previous generations have problematic drifts, causing differences in observation views and response functions for certain objectives at various times (Molling et al., 2010). In summary, the limited number of visible bands, problematic calibration, orbit drifts and other potential problems of AVHRR instruments impose strong restrictions on its applications for aerosol remote sensing over land.

Even though it is challenging work to retrieve aerosol over land from AVHRR observations, impressive progress has been made in the past 20 years. Hauser et al. (2005) extracted surface reflectance from continuous observations over 44 days to retrieve AOD. It has been proven that AOD retrieved from the long-term method is comparable to AERONET and MODIS data; however, the conditions of '45 days' and cloud-free are too strict for the pixel extraction to implement self-improvement and to be implanted into other instruments (Hauser et al., 2005). On this basis, Riffler et al. (2010) improved this algorithm in the estimation of surface reflectance, building an aerosol model and other key parts of retrieval; in particular, a quasi-stand-alone procedure was introduced for post-processing without the support of AERONET data. Mei et al. (2014) revised the VIRvs2.1 used in MODIS DT as VIRvs3.75 (since only the band at 3.75 μm is available for this DT method) after eliminating part of the radiance mixed in the TOA reflectance at 3.75 μm. Then, the regression method was employed to estimate surface reflectance at 0.64 μm to finally retrieve the AOD over the Beijing region successfully. On this basis, Xue et al. (2017) developed an Algorithm for the retrieval over Land of the Aerosol optical Depth (ALAD) and employed it to successfully produce a long-term AOD (0.63 μm) dataset (V1.0) for North China and Central Europe from 1981 to 2015. Meanwhile, DB has been implanted to AVHRR instruments successfully following its application to SeaWiFS, MODIS and VIIRS (Hsu et al., 2004, 2006, 2013, 2017). The Global AVHRR DB dataset (V001) covers 1989–1990 (NOAA-11), 1995–1999 (NOAA-14) and 2006–2011 (NOAA-18), which are expected to expand to all AVHRR instruments and whole-time records. The corresponding global validation work of the initial AVHRR DB dataset (V001) has been conducted by comparing it with the AERONET and MODIS data (Sayer et al., 2017).

This paper aims to evaluate the AVHRR DB V001 dataset over mainland China and analysing the more detailed regional dependency on various conditions. In the first session, data from ground-based networks are used to conduct the overall and regional validation. Immediately following the session is a discussion about the influence of the application of the Angstrom exponent (AE) climatology on aerosol retrieval. The third session is a cross-comparison of AVHRR DB with MODIS DB products. Finally, a brief discussion of this study is provided in the final session.

2. Data and methodology

2.1. DB algorithm and AVHRR DB dataset V001

The purpose of the initial development of the 'Deep Blue' algorithm was to compensate for the disadvantages of missing retrievals over bright surfaces, such as arid, semiarid and urban areas (Hsu et al., 2004) and it was applied to the SeaWiFS instrument successfully, since the pixels with reflectance over 0.15 at the 2.1 μm channel will be eliminated before retrieving. Considering that the reflectance at 'Blue' channels are lower or darker than that at the 'Red' and 2.1 μm channel over a bright surface, DB employs the blue radiance measurement with the algorithm to solve critical values over bright surfaces. The key of the DB algorithm is the building of a reflectivity database at each channel from 412 nm to 865 nm using the minimum reflectivity technique during a certain period. Then, this reflectance database is used for the next processes of aerosol retrieval. Considering that pre-calculated surface databases are inappropriate for vegetated dark areas due to the annual or seasonal surface reflectance that cannot be ignored, the second generation of the DB algorithm employs three surface treatments according to land types to produce global aerosol datasets in MODIS Collection 6 (C6) (Hsu et al., 2013). In the second version of the DB algorithm, pixels are classified into three groups, including arid/semiarid, general vegetated and urban/built-up from MCD 12C1 dataset. For arid/semiarid areas, the typical method of the minimum reflectance database will be performed. For general vegetated areas, the normalized difference vegetation index (NDVI) will be introduced to calculated reflectance by the regression method. For urban/built-up areas, the DB algorithm employs a hybrid approach that combines the NDVI method and pre-calculated surface database for inversion of aerosol properties.

In 2017, the DB algorithm was successfully developed to AVHRR series instruments. As it is well-accepted by the remote sensing community, accurate and precise radiometric measurement is the foundation of quantitative retrieval with high-quality. Limited by the problematic calibration of AVHRR series instruments as discussed above, the DB algorithm adopts an absolute calibration method (Vermote and Kaufman, 1995), which is based on the mature physical mechanism model with low noise (Chander et al., 2013).

The treatment of the surface is the key and primary process in aerosol retrieval for DB. As the improved second generation of DB is applied in MODIS C6, the pixels from AVHRR are filtered into three groups (moderately bright arid and urban regions, general vegetated land surfaces, urban/built-up transitional regions) by land types due to different seasonal/annual varieties of surface reflectivity. Considering the lack of blue channels of AVHRR instruments and higher surface reflectance at 630 nm than those at shorter bands, the ability of DB/AVHRR is restricted to retrieve aerosol over moderately bright arid and