DETECTING LAYER HEIGHT OF SMOKE AND DUST AEROSOLS OVER VEGETATED LAND AND WATER SURFACES VIA OXYGEN ABSORPTION BANDS

Jing Zeng[1], Xiaoguang Xu[1,2], Jun Wang[1], Yi Wang[1], Xi Chen[1], Zhendong Lu[1], Omar Torres[3], Jeffrey S. Reid[4], Steven D. Miller[5]

[1]Department of Chemical and Biochemical Engineering, Center for Global and Regional Environmental Research, and Informatics Initiative, The University of Iowa, Iowa City, Iowa, 52241, USA
[2]Joint Center for Earth Systems Technology and Department of Physics, University of Maryland Baltimore County, Baltimore, Maryland, 21250, USA
[3]Atmospheric Chemistry and Dynamics Laboratory, NASA Goddard Space Flight Center, Greenbelt, Maryland, 20770, USA
[4]Marine Meteorology Division, Naval Research Laboratory, Monterey, California, 93943, USA
[5]Cooperative Institute for Research in the Atmosphere, Colorado State University, Fort Collins, Colorado, 80523, USA

Abstract

We present an algorithm for retrieving aerosol layer height (ALH) and aerosol optical depth (AOD) for smoke and dust over vegetated land and water surfaces from measurements of the Earth Polychromatic Imaging Camera (EPIC) onboard the Deep Space Climate Observatory (DSCOVR). Our algorithm uses EPIC atmospheric window bands to determine AOD and then takes advantage of oxygen A and B bands to derive ALH. We applied this algorithm on several dust and smoke events. Validation shows our results are of high accuracy.

1. Introduction

Absorption of solar radiation by smoke and dust particles can result in diabatic heating, alter atmospheric stability, and affect cloud formation and life cycle. These effects depend critically on the altitude of aerosol layers (Ge et al., 2014; Koch and Del Genio, 2010; Satheesh et al., 2008). An accurate representation of aerosol altitude is thus essential for model prediction of weather and climate (Choi and Chung, 2014; Samset et al., 2013).

Despite the importance of aerosol vertical distribution, the simulation of aerosol layer height (ALH) in current climate models is subject to large inter-model variation and uncertainty (Kipling et al., 2016; Koffi et al., 2012). Frequent satellite observations of global aerosol vertical distribution based on more abundant observation sources are critically needed due to the sparsity of lidar observations over space and time.

The recently-launched Deep Space Climate Observatory (DSCOVR) mission, has introduced an unprecedented opportunity to acquire ALH information multiple times daily. Two of EPIC's bands are located within the oxygen (O_2) "A" and "B" bands (764 nm and 688 nm), each associated with a reference continuum band at 780 nm and 680 nm, respectively. These four bands, offering spectral contrasts between absorption bands and continuum bands (known as the Differential Optical Absorption Spectroscopic, or DOAS, ratios), were originally designed for determining cloud height (Yang et al., 2013). Recently, Xu et al. (2017) presented an algorithm to simultaneously retrieve aerosol optical depth (AOD) and ALH using the EPIC measurements via these four bands and, for the first time, demonstrated EPIC's promising application for determining dust plume height over ocean surfaces during the daytime hours.

The present study, building upon the development of Xu et al. (2017) for determining dust ALH over ocean, extends the algorithm to retrieve ALH from EPIC measurements over land surfaces as well. The augmentation of the Xu et al. (2017) algorithm takes an important additional step towards our goal of providing more frequent global ALH and AOD information for multi-species global aerosol.

2. Remote sensing principle and challenges

The physical principle for sensing of ALH using the O_2 absorption spectroscopic approach, relies on the fact that a scattering aerosol layer can scatter sun light back to space, shortening the path length of a photon traveling in the atmosphere, and reducing the chance of that photon being absorbed by O_2 molecules. As a result, for a given aerosol layer of fixed AOD placed at different altitudes, the higher the altitude, the larger the TOA reflectance. However, in reference continuum bands, the TOA reflectance is not sensitive to ALH but depends only on the column AOD, thus the ratio of TOA reflectance between in-band and continuum band, or the DOAS ratio, provides a practical way to infer the ALH (e.g., Dubuisson et al., 2009; Duforêt et al., 2007; Xu et al., 2017).

To build the links between DOAS ratios and ALH, we simulate TOA reflectance as observed by EPIC measurements with the state-of-the-art Unified Linearized Vector Radiative Transfer Model (UNL-VRTM, https:// unl-vrtm.org), which is a radiative transfer testbed developed specifically for atmospheric remote sensing (Wang et al., 2014).

We found the DOAS ratios in general increase with the rise of ALH, but the sensitivity of DOAS to ALH is higher for lower surface reflectance and larger AOD. As a result, our algorithm can only retrieve ALH over water and vegetated surfaces due to their low surface reflectance. Additionally, retrieval of ALH requires a sufficiently high aerosol loading.

3. EPIC aerosol layer height retrieval algorithm

Briefly, the retrieval algorithm entails the following steps:

1. Calculate TOA reflectance in six EPIC visible and NIR bands (443, 551, 680, 688, 764, and 780 nm) from the calibrated EPIC level 1B digital data.

2. Identify EPIC pixels that are suitable for aerosol height retrieval. Through various tests, this step screens out pixels having clouds, over-water sun glints, and bright land surfaces, which are performed separately for water and land pixels. Surface pressure comes from MERRA-2 reanalysis data and we determine surface reflectance in EPIC bands using GOME-2 and MODIS surface products.

3. Aggregate the original EPIC pixels into a box of 3×3 individual pixels, an area with size of about 24 km at nadir. In many cases, not all pixels within a box are suitable for retrieval (i.e., cloud, glint, and bright land). If the number of available pixels within a box is not less than 4 (of the total of 9), calculate mean values of TOA reflectance, satellite geometries, and surface reflectance for the

available pixels. Otherwise, do not conduct an aerosol retrieval for the box.

4. Invert the aggregated EPIC observations using pre-calculated lookup tables to obtain smoke ALH and AOD. The inversion uses a flexible spectral fitting strategy that considers the specific surface type.

While the retrieval procedure is based on our algorithm of retrieving dust ALH over ocean from EPIC measurements (Xu et al., 2017), it was upgraded in several ways, including implementing smoke aerosol optical properties, land surface characterization, and more robust strategies for the procedures of pixel selection and spectral fitting.

4. Retrieval demonstration and validation

We apply our algorithm to six EPIC scenes over the Hudson Bay – Great Lakes area obtained during 25 – 26 August 2017, with three consecutive scenes considered on each day. There would be more case studies in our further research.

Obvious spatial variations are noted in retrieved smoke ALH and AOD. On August 25, smoke plumes had AOD values ranging from 0.1 to 0.45, with higher loading found at downwind regions in the south. An ALH of 4 – 5 km was found over Hudson Bay, whereas the smoke altitudes decreased to 2 – 4 km over land off the bay's western and southern shores. Southward, the ALH increased rapidly to 4 – 6 km towards the Great Lakes. By August 26, the smoke plumes had traveled southeast. The smoke altitudes remained at 3 – 5 km over the eastern part of Hudson Bay, and 2 – 4 km over the bay's south side. Altitudes of smoke plumes over the coast of northeastern U.S. were higher than 5 km. Aside from spatial variations, the retrievals also revealed diurnal changes of ALH and evolution of the smoke plumes. For instance, the ALH of smoke plumes over the Hudson Bay and the north side of the Great Lakes rose by about 0.5 km within 2 hours from local morning to afternoon on August 25.

Validation is performed against aerosol extinction profiles detected by the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) and against AOD observed at nine Aerosol Robotic Network (AERONET) sites, showing, on average, an error of 0.58 km and a bias of -0.13 km in retrieved ALH and an error of 0.05 and a bias of 0.03 in retrieved AOD. Additionally, we show that the aerosol height information retrieved by the present algorithm can potentially benefit the retrieval of aerosol properties from EPIC's ultraviolet (UV) bands.

5. References

[1] Choi, J.-O., and Chung, C. E.: Sensitivity of aerosol direct radiative forcing to aerosol vertical profile, *Tellus B*, 66, 24376, 2014.

[2] Dubuisson, P., Frouin, R., Dessailly, D., Duforêt, L., Léon, J.-F., Voss, K., and Antoine, D.: Estimating the altitude of aerosol plumes over the ocean from reflectance ratio measurements in the O2 A-band, *Remote Sensing of Environment*, 113, 1899-1911, 2009.

[3] Duforêt, L., Frouin, R., and Dubuisson, P.: Importance and estimation of aerosol vertical structure in satellite ocean-color remote sensing, *Appl. Opt.*, 46, 1107-1119, 2007.

[4] Ge, C., Wang, J., and Reid, J. S.: Mesoscale modeling of smoke transport over the Southeast Asian Maritime Continent: coupling of smoke direct radiative effect below and

above the low-level clouds, *Atmos. Chem. Phys.*, 14, 159-174, 2014.

[5] Kipling, Z., Stier, P., Johnson, C. E., Mann, G. W., Bellouin, N., Bauer, S. E., Bergman, T., Chin, M., Diehl, T., Ghan, S. J., Iversen, T., Kirkevåg, A., Kokkola, H., Liu, X., Luo, G., van Noije, T., Pringle, K. J., von Salzen, K., Schulz, M., Seland, Ø., Skeie, R. B., Takemura, T., Tsigaridis, K., and Zhang, K.: What controls the vertical distribution of aerosol? Relationships between process sensitivity in HadGEM3–UKCA and inter-model variation from AeroCom Phase II, *Atmospheric Chemistry and Physics*, 16, 2221-2241, 2016.

[6] Koch, D., and Del Genio, A. D.: Black carbon semi-direct effects on cloud cover: review and synthesis, *Atmos. Chem. Phys.*, 10, 7685-7696, 2010.

[7] Koffi, B., Schulz, M., Bréon, F.-M., Griesfeller, J., Winker, D., Balkanski, Y., Bauer, S., Berntsen, T., Chin, M., Collins, W. D., Dentener, F., Diehl, T., Easter, R., Ghan, S., Ginoux, P., Gong, S., Horowitz, L. W., Iversen, T., Kirkevåg, A., Koch, D., Krol, M., Myhre, G., Stier, P., and Takemura, T.: Application of the CALIOP layer product to evaluate the vertical distribution of aerosols estimated by global models: AeroCom phase I results, *Journal of Geophysical Research: Atmospheres*, 117, D10201, 2012.

[8] Samset, B. H., Myhre, G., Schulz, M., Balkanski, Y., Bauer, S., Berntsen, T. K., Bian, H., Bellouin, N., Diehl, T., Easter, R. C., Ghan, S. J., Iversen, T., Kinne, S., Kirkevåg, A., Lamarque, J. F., Lin, G., Liu, X., Penner, J. E., Seland, Ø., Skeie, R. B., Stier, P., Takemura, T., Tsigaridis, K., and Zhang, K.: Black carbon vertical profiles strongly affect its radiative forcing uncertainty, *Atmos. Chem. Phys.*, 13, 2423-2434, 2013.

[9] Satheesh, S. K., Moorthy, K. K., Babu, S. S., Vinoj, V., and Dutt, C. B. S.: Climate implications of large warming by elevated aerosol over India, *Geophysical Research Letters*, 35, L19809, 2008.

[10] Wang, J., Xu, X., Ding, S., Zeng, J., Spurr, R., Liu, X., Chance, K., and Mishchenko, M.: A numerical testbed for remote sensing of aerosols, and its demonstration for evaluating retrieval synergy from a geostationary satellite constellation of GEO-CAPE and GOES-R, *Journal of Quantitative Spectroscopy and Radiative Transfer*, 146, 510-528, 2014.

[11] Xu, X., Wang, J., Wang, Y., Zeng, J., Torres, O., Yang, Y., Marshak, A., Reid, J., and Miller, S.: Passive remote sensing of altitude and optical depth of dust plumes using the oxygen A and B bands: First results from EPIC/DSCOVR at Lagrange-1 point, *Geophysical Research Letters*, 44, 7544-7554, 2017.

[12] Yang, Y., Marshak, A., Mao, J., Lyapustin, A., and Herman, J.: A method of retrieving cloud top height and cloud geometrical thickness with oxygen A and B bands for the Deep Space Climate Observatory (DSCOVR) mission: Radiative transfer simulations, *Journal of Quantitative Spectroscopy and Radiative Transfer*, 122, 141-149, 2013