We thank the Reviewers for their very thorough and constructive comments, which have helped to improve the quality of this paper. Below are our responses to their comments. The response (e.g., blue) follows each comment.

Comments from the editors and reviewers:

This paper introduces an algorithm for the determination of the cloud top pressure inferred from measurements of oxygen absorption in the NIR by the EPIC sensor onboard the DSCOVR platform. The topic is important and appropriate for the journal.

The paper shows some sound science and the authors have structured their manuscript in the correct way. All major sections needed to present a retrieval algorithm are, in my opinion, addressed. However, major improvements are still needed, and I will be willing to evaluate a revised version of the paper. I bullet-list improvements and remarks "general comments" section and then I delve in the explanation of specifics later on.

*** General main comments

- Before any scientific content scrutiny, I suggest to thoroughly check punctuation, syntax and word C-(c)-apitalization and arrangement prior publication. Copernicus service should definitely help here, but also and foremost checks by the English native coauthors. Uneven sentences or awkward wording are present throughout the manuscript and are too many to be listed by a referee. This will help to showcase the logic of the method and the importance of the results.

- In the introduction state clearly and make explicit the difference with Yang et al. JQSRT, 2013. As both papers share the same goal, data source and co-authors, it is important to highlight the advancement achieved in this paper with respect to previous literature. Some scientific insights about the difference between the A and the B-band are given in Yang et al. but are put to little of any use in this work. One would expect some science advancement and not a mere application or repetition of a method. All my criticism and required improvements naturally follow from this remark.

Author reply: In the revised manuscript, we have added some sentences to describe the scientific insights about Yang et al. JQSRT, 2013, which are shown as follows:

"…By using EPIC reflectance ratio data at oxygen A-band and B-band absorption to reference channels, Yang et al. (2013) developed a method to retrieve CTH and cloud geometrical thickness simultaneously for fully cloudy scene over ocean surface. First their method calculates cloud centroid heights for both A- and B-band channels using the ratios between the reflectance of the absorbing and reference channels, then derives the CTH and the cloud geometrical thickness from the two dimensional look up tables that relate the sum and the difference between the retrieved centroid heights for A- and B-bands to the CTH and the cloud geometrical thickness. The difference in the O_2 A- and B-band cloud centroid heights is resulted from the different penetration depths of the two bands. Compared to the cloud height variability, the penetration depth differences are much smaller and the retrieval accuracy from this method can be affected by the instrument noise (Davis et al. 2018a, b)."

Compared to Yang et al. (2013), this paper uses an analytical method to address the issue of in-cloud penetration. This approach is less prone to errors caused by instrument noise and the results are more robust. In this paper, the analytical method "adopted ideas of the semi-analytical model (*Kokhanovsky and Rozanov, 2004; Rozanov and Kokhanovsky, 2004*), and developed a quadratic EPIC analytic radiative transfer equation to analyze the radiative transfer in oxygen A- and B-band channels."

- Therefore, the treatment of aerosols is overly simplified or neglected together with error analysis as function of cloud optical thickness or cloud cover, since we know that from the remote sensing perspective these two quantities are connected.

Author reply: In the revised paper, we have added some comments to describe the aerosol extinction issue. The detailed information is shown in the replies of later questions.

- The coefficients A, B, C (P6 L199) must be presented otherwise the reader is not equipped with the knowledge to replicate the results.

Author reply: We have presented coefficients A, B, C in Equation 13 in the revised paper.

- The presentation and analysis of the results is suboptimal. Without proper and customary validation with external independent data sets little knowledge can be won about the applicability ranges of the presented method in real geophysical scenarios, which is one of the stated goals of the paper, otherwise Section 5 would not be presented.

Author reply: In the revised paper, we have added a new subsection 3.2, i.e., validation of the retrieval method. We used the cloud layer top pressure information from CALIPSO measurements as a reference to validate our retrieval method. Through the case of validation, we obtain the following results: "… under single layer cloud situations, the CTPs derived from EPIC measurements are close to the CTP from CALISPO; under multi-layer cloud situations, the CTP derived from EPIC measurements are larger than the CTP from CALISPO…. For these single layer cloud cases, the mean values of CTP of CALIPSO, EPIC effective, EPIC baseline and EPIC retrieval are 846, 834, 866 and 850 mb, respectively. Compared to the CTP from CALIPSO measurements , the EPIC effective and baseline CTPs are 12 mb smaller or 20 mb larger, respectively; the EPIC retrieval with consideration of photon penetration is only 4 mb larger. This shows that our method for the CTP retrieval is valid and accurate under single layer cloud situations with COD > 3 and low surface albedo. Under multi-level cloud situations, the high-level clouds are often thin clouds, which can be detected by CALIPSO but hard to derive by our retrieval method. It is because the EPIC retrieved CTP mainly shows the pressure of cloud layer that reflects the major part of incident sun light."

*** Specific comments to individual sections

- Abstract

P1 L28: why "obviously"? It is not a straightforward inference and it is not objective, but subjective instead. Please, remove it from the abstract.

Author reply: We have removed it as suggested.

P1 L29-30: could you provide quantitative figures for the comparisons? Something like "Out of N cases, we found an average bias between CTP b- and A-band of xxx hPa _xxx hPa_stdv".

Author reply: We have added this sentence into the abstract as suggested.

"…Out of around 10000 cases, in retrieved CTP between A- and B-bands we found an average bias of 93 mb with standard deviation of 81 mb."

P2 L44: "their atmospheric profiles"? You may want to check this, because the atmospheric profile is the same. You are simply converting between quantities based on the P-T levels.

Author reply: We have revised it to "the related atmospheric profile".

P2 L46: you may want to cite the Yamamoto-Wark paper as first historical record of CTP retrieval from oxygen absorption.

Author reply: We have cited the Yamamoto-Wark paper as suggested.

P2 L49-50: "Many approaches are designed to retrieve clouds' effective top pressures without considering their in-cloud photon penetration, and therefore derive effective top pressures higher than CTP."

I have two remarks for this statement.

1) there are other approaches taking into consideration in-cloud photon penetration. They must be correctly cited. Notably, analytical radiative transfer has been implemented by Kokhanovsky and Rozanov, JQSRT 2004 (forward problem) and Rozanov and Kokhanovsky, JGR 2004 (inverse problem) and globally deployed and validated by Lelli et al, AMT, 2012 and Lelli et al. ACP 2014. For the LUT method, the reference is Loyola et al. AMT 2018. So please, cite this literature.

Author reply: In the revised paper, we have cited these literatures and another paper Richardson and Stephens (2018):

"Although the theory of using oxygen absorption bands to retrieve CTP was proposed decades ago (Yamamoto and Wark, 1961), it is still very challenging to do the retrieval accurately due to the complicated in-cloud penetration effect (Yang et al., 2019, 2013; Davis et al., 2018a, 2018b; Richardson and Stephens, 2018; Loyola et al., 2018; Lelli et al., 2014, 2012; Schuessler et al., 2013; Rozanov and Kokhanovsky, 2004; Kokhanovsky and Rozanov, 2004; Kuze and Chance, 1994; O'brien and Mitchell, 1992; Fischer and Grassl, 1991; and etc.)….. In the meantime, to improve the retrieval accuracy of CTP, various techniques have been applied to the retrieval methods with in-cloud photon penetration. For example, Kokhanovsky and Rozanov (2004) proposed a simple semi-analytical model for calculation of the top-of-atmosphere (TOA) reflectance of an underlying surface-atmosphere system, accounting for aerosol and cloud scattering. Based on the work of Kokhanovsky and Rozanov (2004), Rozanov and Kokhanovsky (2004) developed an asymptotic algorithm for the CTH and the geometrical thickness determination using measurements of the cloud reflection function. This retrieval method was applied by Lelli et al. (2012, 2014) to derive CTH using measurements from GOME instrument on board the ESA ERS-2 space platform."

Richardson, M. and Stephens, G.L., 2018. Information content of OCO-2 oxygen A-band channels for retrieving marine liquid cloud properties. *Atmospheric Measurement Techniques*, *11*(3), pp.1515-1528.

2) The authors assume that the reader already knows the scientific reasoning behind the CTP overestimation / CTH underestimation. Which might not be true. So, please, explain here why the neglection of photon penetration and multiple scattering within the cloud gives rise to this effect.

Author reply: In the revised paper, we have added the following two sentences:

"…To estimate the CTP from satellite measurements, many approaches have been designed to retrieve clouds' effective top pressures without considering in-cloud photon penetration. These approaches did not consider light penetrating cloud, therefore the derived CTH is lower than the cloud top, and the effective top pressures is higher than CTP…."

P2 L 67-68: "the differences between in-band and reference band are negligible". This statement cannot be generalized. So, please add "at nominal EPIC response functions" or similar.

Author reply: We have revised it as suggested.

P3 L 86-87: "the ratios of absorption/reference are less impacted by the instrument calibration and other measurement error." I might agree with this statement if the authors can provide at least a reference to some EPIC assessment reports or papers where absolute (nor relative neither ratioed) calibration and degradation of the NIR channels are provided. I tend to believe it is the case but I would like to have this information at hand for sake of consistency.

Author reply: Currently, we do not find the exact statements from reference literature to present this comment. But we can draw the conclusion from the studies of Marshak et al. (2018).

Marshak, A., J. Herman, A. Szabo, K. Blank, S. Carn, A. Cede, I. Geogdzhaev, D. Huang, L.-K. Huang, Y. Knyazikhin, M. Kowalewski, N. Krotkov, A. Lyapustin, R. McPeters, K. Meyer, O. Torres and Y. Yang, 2018. Earth Observations from DSCOVR/EPIC Instrument. *Bulletin Amer. Meteor. Soc. (BAMS)*, 9, 1829-1850, https://doi.org/10.1175/BAMS-D-17-0223.1.

According to this paper, the calibration of EPIC measurements consists of two steps: (1) From Level-0 data, raw EPIC data (counts per second), to Level-1A "corrected count rates". This step includes 6 steps, such as dark offset correction, nonlinear correction, temperature correction, stray-light corrections, and etc. (2) Geolocation algorithms from Level 1A to Level 1B. To convert the count rates to reflectance data, calibration factors are needed. The reflectance calibration is implemented by using other satellite instruments like OMPS and MODIS. For example, EPIC 680 and 780 nm channels use MODIS to obtain calibration factor K_λ. For oxygen A-and B-band channels, lunar observations are used for calibration. "Lunar reflectance R_λ does not increase much with a small wavelength change $\Delta\lambda$; a 10-nm difference in λ leads to a difference in R_λ in the range of 0.0006–0.0013 or 0.8%–1.2% (e.g., Ohtake et al. 2010, 2013). …"

"…Indeed, the ratio $F(\lambda_1, \lambda_2)$ of the lunar reflectance values measured in counts per second at two neighboring channels λ_1 and λ_2 is very stable…." The calibration factors of 688 and 764 nm are calculated as follows (Geogdzhayev and Marshak, 2018):

Geogdzhayev, I. and A. Marshak, 2018. Calibration of the DSCOVR EPIC visible and NIR channels using MODIS Terra and Aqua data and EPIC lunar observations. *Atmos. Meas. Tech.* 11, 359 -368, https://doi.org/10.5194/amt-11-359-2018

$$K_{688} \approx \frac{K_{680}}{F(680{,}688)};\ K_{764} \approx \frac{K_{780}}{F(780{,}764)}$$

From the above calibration processes, we can get the following information:

(1) For EPIC oxygen A- and B-band channels, we need a series of calibration to obtain the reflectance data, which accuracy is impacted by many factors. Take 688 nm channel, as an example; its accuracy is impacted by the preprocessing calibration error, accuracy of K_{680} and $F(680{,}688)$.

(2) For the ratio of absorption/reference (e.g.., R_{688}/R_{680}): because all EPIC channels share the same optical system and the same CCD sensors, some preprocessing calibration errors can be reduced when we calculate the ratio of two channels. For the R_{688}/R_{680}, the impact of accuracy of K_{680} is eliminated, because it is only determined by $\frac{K_{680}}{K_{688}}$ $or\ F(680{,}688)$.

Therefore, we can say: "the ratios of absorption to reference channels are less impacted by the instrument calibration and other measurement error." We have updated the manuscripts as follows:

"…Also, compared to any specific EPIC oxygen absorption bands (i.e., R_{764} and R_{688}), the ratios of absorption to reference channels (i.e., R_{764}/R_{779} and R_{688}/R_{680}) are less impacted by the instrument calibration and other measurement error. This can be explained by the following reasons: First, the EPIC measurements at oxygen A and B absorption and reference bands share same sensor and optical system, when calculating the ratios of them, some preprocessing calibration errors can be reduced. Second, to calculate R_{764} and R_{688}, the ratio of lunar reflectance at neighboring channels (i.e., $F(764{,}779)$ and $F(688{,}680)$) and the calibration factors of oxygen A and B reference bands (i.e., K_{779} and K_{680}) are used (Geogdzhayev and Marshak , 2018; Marshak et al., 2018). Therefore, the accuracy of R_{764} and R_{688} is determined by the stability of $F(764{,}779)$ and $F(688{,}680)$ and the accuracy of K_{779} and K_{680} together. But the accuracy of absorption to reference ratios is only determined by the stability of $(764{,}779)$ and $F(688{,}680)$."

Still Section -2- does not mention any surface influence. We know that the continuum at 779 nm is impacted by the red edge, whereas the b-band is not. So, I find myself left with the doubt: are the authors aware of this?

Author reply: Thank you for reminding the issue of red-edge. We have added a comment about it into the revised paper as follows: "…It is worth noting that for EPIC measurements at both oxygen A- and B-bands, the surface influence cannot be ignored. For examples, in the snow or ice covered area the surface albedo is high; in the plants covered area, the surface albedo changes substantially between oxygen A-band and B-band due to the impact of spectral red-edge (*Seager et al., 2005*)."

P3 Figure 1: Can the authors provide here in the caption or in the text the details of the simulation for these oxygen spectra? Mainly observational geometry, aerosol total load, ozone concentration and surface reflectivity/albedo?

Author reply: In Figure 1, the absorption optical depth spectrum at the oxygen A and B bands is only related to the oxygen absorption coefficients and the atmospheric model. We have added some detailed information about simulation into the revised paper, which is shown as follows:

"…The high resolution absorption optical depth spectrum at oxygen A-band and B-band is calculated by Line-By-Line Radiative Transfer Model (LBLRTM, *Clough et al., 2005*) with HITRAN 2016 database (*Gordon et al., 2017*) for the U.S. standard atmosphere. "

P4 L106-107: "Cloud pressure thickness can be estimated with cloud optical thickness using statistical rules." Which are? Can the authors explain what statistical rules are they referring to and the physical principles behind this statement? References are also welcome along the way (this remark has to be read jointly with the remarks for Section 4.4 below).

Author reply: In this study, the retrieval method cannot retrieve the cloud pressure thickness with CTP simultaneously, and it considers the cloud pressure thickness as an input parameter for CTP retrieval. We will improve our method to address this issue in the future.

Currently, we use cloud optical thickness to estimate cloud pressure thickness by using NASA atmospheric reanalysis data. In the revised manuscript, we have added detailed comments to state how we use cloud optical thickness to estimate the cloud pressure thickness:

"…The cloud pressure thickness or the cloud vertical distribution has substantial impact on the accuracy of the CTP retrievals (*Carbajal Henken et al., 2015; Fischer and Grassl, 1991; Rozanov and Kokhanovsky, 2004; Preusker and Lindstrot, 2009*). In this study, the cloud pressure thickness is used as an input parameter to retrieve the CTP. However, no related accurate cloud pressure thickness is provided by other satellite sensors now. To constrain the error from the estimation of cloud pressure thickness, we relate it to the cloud optical thickness. It is reasonable because clouds with higher optical thickness normally have higher values of pressure thickness. To explore the correlation between cloud pressure thickness and cloud optical thickness, we use the related cloud data from Modern-Era Retrospective analysis for Research and Applications Version 2 (MERRA-2, Gelaro et al., 2017), which is a NASA atmospheric reanalysis for the satellite era using the Goddard Earth Observing System Model Version 5 (GEOS-5) with Atmospheric Data Assimilation System (ADAS).

Based on statistical analysis of one year's single-layer liquid water clouds over an oceanic region (S23.20, W170.86, S2.11, W144.14) in 2017, we can get an equation for cloud pressure thickness approximation, i.e., cloud pressure thickness (mb) = 2.5* COD + 23. The derived correlation coefficients are dependent on the case region and time selections. Due to the complexity of cloud vertical distribution, whatever the accuracy of the correlation coefficients is, the estimation will certainly bring in error."

The scatter plot of cloud pressure thickness and cloud optical thickness is shown in Figure R1. (After re-checking the cloud data, we updated the equation as: cloud pressure thickness (mb) = 2.5* COD + 23.)

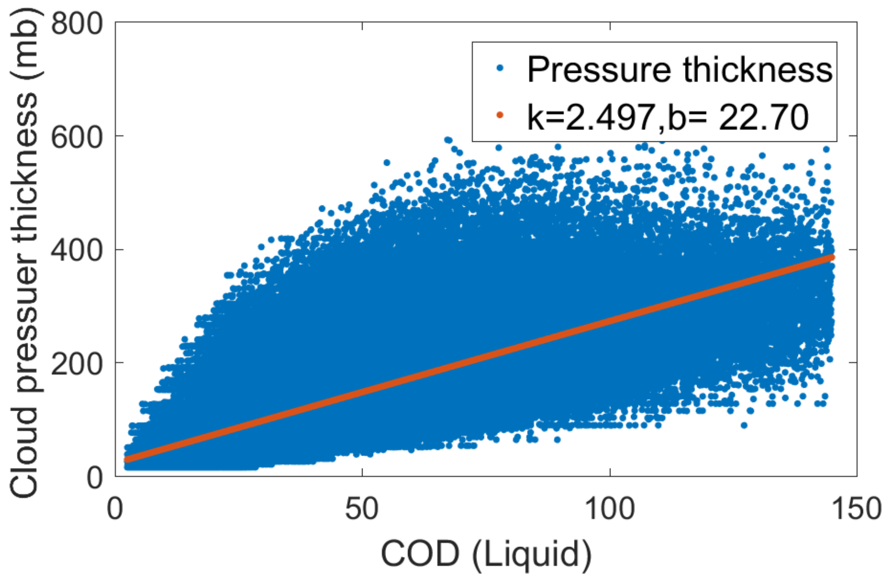


Figure R1. The scatter plot of cloud pressure thickness and cloud optical depth and the related linear fitting line.

P4 L 108-110: "It is worth noting that certain variables will have a non-linear effect on EPIC observations, however, these variations occur smoothly." Well, never poke a bear: could you please explain what are the variables smoothly having a non-linear effect on EPCI observations? First, what observations? Second, are these variables of radiometric or geometric origin? Are they clouds themselves? What kind of non-linear relationship are the authors thinking at? And if it a smooth one, this means it has been already well characterized. Would you provide some figures or references as well?

Author reply: Maybe this sentence is ambiguous and make readers confuse. The original meaning of it is shown as follows: the "ratio of simulated reflectance measurements for EPIC absorption/reference" is a function of multiple variables, i.e., surface albedo, cloud optical depth, solar zenith angle, cloud top pressure and cloud pressure thickness. The effects of these variables on that ratio may be not linear, such as COD, as shown in Figure 3 in the manuscript. If the resolution of the LUT is high, we still can use linear interpolation method to retrieve the unknown variable with high accuracy. Take a simple example, for an exponential function y=exp (x), y is not a linear function of x, but if we have a series of pair values (x_i,y_i) in the range of x = [1,4] with high resolution (e.g., 0.02), we still can calculate exp (3.535) with pretty high accuracy by using linear interpolation method to exp(3.52) and exp (3.54). We have revised this sentence in the manuscript:

"…It is worth noting that the reflectance ratio of absorption/reference can be seen as a function of surface albedo, solar zenith and viewing angles, COD, CTP and cloud pressure thickness. Some atmospheric variables have a non-linear effect on the reflectance ratio. For example, the reflectance ratio is more sensitive to the variation of COD when COD is small. Overall, the reflectance ratio varies monotonically and smoothly with these variables (shown in Figure 3). With a relatively high-resolution simulated table, we can use a localized linear interpolation method to estimate the proper values…"

P4 L114-116: "In physics, the retrieval accuracy is impacted by two main uncertainty sources: (1) the limited ability of EPIC in identifying cloud thermodynamic phase, which will affect the accuracy of cloud optical thickness retrieval, and 2) the uncertainty in estimating Cloud pressure."

Yes correct. But this is disconnected from the sentence above about the interpolation error and the sentence here reads as a filler. So, I suggest to either expand this paragraph and describe thoroughly how the total error in CTP splits into random and systematic components, model and retrieval errors, and what originates them or, please, remove this sentence. Also because Section 3.1 is just about the LUT method. Ah, by the way, it would be very insightful to substantiate with numbers or references the LUT interpolation error component. Your choice.

Author reply: We have removed this sentence as suggested. We also added more comments about the LUT based approach with some references. Parts of the revised paragraph are shown as follows:

"One commonly used method of retrieval for satellite observation is through the building and usage of LUTs (Loyola et al., 2018, Gastellu-Etchegorry and Esteve, 2003). LUT based approach can be fast because the most computationally expensive part of the inversion procedure is completed before the retrieval itself. For DSCOVR EPIC observations, we can build LUTs by simulating EPIC measurements under various atmospheric conditions, such as different surface albedo, solar zenith and viewing angles, COD, CTP, and cloud pressure thickness. Comparing the related simulated reflectance at the oxygen absorption and reference bands, we can obtain two LUTs for reflectance ratios of absorption/reference at EPIC oxygen A-band and B-band respectively, which can be used for the CTP retrieval. The detailed information of simulated reflectance ratio of absorption/reference is stated in Section 2.3.3. …"

"….The retrieval error of this method is determined by the resolution of the LUT, i.e., the higher the resolution, the higher retrieval accuracy. However, for multiple dimensional LUTs, the increase of resolution will increase the table size exponentially, which will increase computational cost substantially for the table building and inverse searching. Another possible method to increase the retrieval accuracy is using different interpolation methods. For example, if the value of LUT varies non-linearly with a variable, using high order interpolation method maybe better than using linear interpolation method (Dannenberg, 1998)."

P5 L145-146 and ff: "However, their attenuations from Rayleigh scattering and aerosol extinction are close to each other. Thus ... " I am personally not satisfied by these reoccurring statements in the manuscript. Too general, subjective and overly simplyfing. As such, the inference that photon path length can be derived by ratioing continuum and in-band channels does not follow from that. If you invert the logic, would the converse hold? Saying that molecular and aerosol extinction are not "close to each other" would still CTP retrieval be feasible? I would say it does. So, the issue here is that the authors simply avoid aerosol description for the sake of simplicity, but it is not what one would expect from an algorithm.

Author reply: We have revised this sentence as follows:

"...Oxygen A-band and its reference band are also attenuated by airmass and aerosol through Rayleigh scattering and aerosol extinction. In the standard atmospheric model, the optical depth of Rayleigh scattering (τ_{Ray}) at oxygen A-band (B-band) and its reference band is 0.026 (0.040) and 0.024 (0.042), respectively (Bodhaine et al., 1999). The absolute difference of Rayleigh scattering optical depth ($\Delta\tau_{Ray} = \tau_{Ray}^{In-band} - \tau_{Ray}^{Ref}$) between them is within 0.002. Compared to Rayleigh scattering, the difference of background aerosol optical depth ($\Delta\tau_{Aer}$) between absorbing and reference bands is smaller, within 0.0005. Therefore, the attenuations from Rayleigh scattering and aerosol extinction at EPIC oxygen absorption and its reference band are close to each other. Thus, when we use the ratio of EPIC measured reflectance at oxygen A-band and its reference band to derive the photon path length distribution and retrieve cloud information such as CTP, the impact of Rayleigh scattering and aerosol extinction can be simplified in the analytic transfer inverse model."

We also revised Eq. (11) to show the impact of background extinction.

"Combining Eqs. (2), (9) and (10), we can get the total EPIC analytic transfer equation as follows

$$-log\left(\frac{R_A}{R_f}\right) = f\left(\Delta\tau_{O2}^{Above-Cld},\ \mu_0, \mu, \varphi\right) + f\left(\tau_{O2}^{Top}, \Delta\tau_{O2}^{Cld}, \mu_0, \mu, \varphi\right) + f\left(\Delta\tau_{O2}^{Below-Cld},\ \mu_0, \mu, \varphi\right) + \Delta\tau_{BG}\left(\frac{1}{\mu} + \frac{1}{\mu_0}\right) \quad (11)$$

In Eq. (11), $\Delta\tau_{BG}$ represents the sum of optical depth difference of background extinction (i.e., Rayleigh scattering $\Delta\tau_{Ray}$, aerosol extinction $\Delta\tau_{Aer}$, and O3 $\Delta\tau_{O3}$) between oxygen in-band and reference band, as shown in Eq. (12).

$$\Delta\tau_{BG} = \ \Delta\tau_{Ray} + \ \Delta\tau_{Aer} + \Delta\tau_{O3} \quad (12)$$

As stated in the previous subsection, in the standard atmospheric model with background aerosol loading, ($\Delta\tau_{Ray}$, $\Delta\tau_{Aer}$, $\Delta\tau_{O3}$) is approximately (0.002, 0.0005, −0. 0005) and (-0.002, -0.0005, -0.002) respectively at oxygen A and B bands, thus $\Delta\tau_{BG}$ is approximately 0.002 and −0.0045 respectively at these two bands."

P5 L149-151: Please, refrain from wording like "and etc." and try to be rigorous. Assumptions are fine, as long as they are clearly presented and justified by a scale analysis or a scientific reasoning. So, please enumerate all assumptions you make and justify each of them.

Author reply: We have revised this sentence: "To simplify the analytic transfer inverse model for EPIC observations, we made a series of assumptions, e.g., isotropic component, a plane-parallel homogenous cloud assumption with quasi-Lambertian reflecting surfaces. These assumptions have been widely used in radiative transfer calculation for cloud studies."

P5 and ff: could you please use the standard \tau symbol for optical depth throughout the paper? \t can be misinterpreted as transmission.

Author reply: We have revised it, as suggested, by using τ to replace \t.

P7 L215: missing to introduce the \k_i in the text. Please, correct.

Author reply: We have defined k_i in the revised manuscript: …k_i is the line shapes of oxygen A- and B-bands.

P7 L222 and ff: How does Eq.14 relate to the conversion between CTP and CTH?

Author reply: The Eq.16 (i.e., Eq.14 in the original manuscript) is used to calculate oxygen absorption coefficients for any given atmospheric profiles. It is not directly related to the conversion between CTP and CTH. In this paper, we mainly focus on the retrieval of CTP and all discussions are mainly focused on the CTP too. We have revised the related paragraph as follows:

"In the simulation of EPIC measurements, the atmospheric layer at a given layer-average pressure can have drastically different temperature depending on the atmospheric profile in use. To ensure the accuracy of simulation, we need to use the LBLRTM package to calculate oxygen absorption coefficients for each pressure/temperature profile, which is a time-consuming process. Our goal has been to find a simple and fast method to calculate oxygen absorption coefficients for different atmospheric profiles. Based on the study of Chou and Kouvaris (1986), Min et al. (2014) proposed a fast method to calculate oxygen absorption optical depth for any given atmosphere by using a polynomial fitting function, as shown in Eq. (16).

$$\ln\left(A_{vLM}\right) = \left[a_0(v,P) + a_1(v,P) \times (T_{LM} - T_{mL}) + a_2(v,P) \times (T_{LM} - T_{mL})^2\right] \times \rho_{O_2} \quad (16)$$

Where A_{vLM} is optical depths for layer L, spectral point v, and atmosphere model M; ρ_{O_2} is molecular column density ($\frac{molecules}{cm^2} \times 10^{-23}$); T_{LM} is the average temperature for layer L for a given atmosphere; and T_{mL} is average temperature over all six typical geographic-seasonal model atmospheres (M1 to M6, i.e., tropical model, mid-latitude summer model, mid-latitude winter model, subarctic summer model, subarctic winter model, and the U.S. Standard (1976) model) for layer L. To derive the coefficients a_0, a_1, and a_2, we first calculated oxygen optical depth coefficients for all typical atmospheres (M1 to M6) by using LBLRTM package, and then selected three of them (e.g., M1, M5, and M6) to calculate the polynomial fitting coefficients. This method has been successfully used by Min et al. (2014) to simulate the high resolution oxygen A-band measurements."

Please, expand and/or reword this paragraph clearly exposing the practical usage of this relationship w.r.t. cloud parameters to be retrieved. Also, what are the nM_i (i=1...6) model atmospheres? Are you subsetting a yearly cycle in six different model atmospheres? Are you slicing after zonal bands?

Author reply: We did not subset a yearly cycle in six different model atmospheres or slice after zonal bands. We have revised this paragraph as shown in the answer to the last question.

"…Where A_{vLM} is optical depths for layer L, spectral point v, and atmosphere model M; ρ_{O_2} is molecular column density ($\frac{molecules}{cm^2} \times 10^{-23}$); T_{LM} is the average temperature for layer L for a given atmosphere; and T_{mL} is average temperature over all six typical geographic-seasonal model atmospheres (M1 to M6, i.e., tropical model, mid-latitude summer model, mid-latitude winter model, subarctic summer model, subarctic winter model, and U.S. Standard (1976) model) for layer L. To derive the coefficients a_0, a_1, and a_2, we first calculated oxygen optical depth coefficients for all typical atmospheres (M1 to M6) by using LBLRTM package, and then selected three of them (e.g., M1, M5, and M6) to calculate the polynomial fitting coefficients. This method has been successfully used by Min et al. (2014) to simulate the high resolution oxygen A-band measurements."

P8 Equation 16: please be rigorous and consistent through the paper. Here you use \t as temperature, while \t was optical depth in the previous sections. So, temperature is \T, optical depth is \tau. Also, capital \H is not present in the equation. For the time being let me assume that the y-axis displays the following quantity:

100*(LBL - DBL_K)/LBL.

Author reply: We have changed "*t*" to "*T*" to represent temperature. The capital *H* has been changed to *h*. The y-axis displays the relative difference: 100*(DBL_K-LBL)/LBL.

Also, without information about aerosol in the simulations, these results indicate that molecular scattering introduces a systematic bias, as can be seen in the continuum outside absorption. For the in-band channels, however, the sign of the residuals reverses.

This points to a different treatment of oxygen layered extinction. From the perspective of the CTP retrieval, what counts is the ratio of the channels. Given Fig.2 and the definition of the residuals introduced above, my guess is that you are overestimating molecular scattering and underestimating oxygen absorption.

This translates into a quenched ratio between continuum and in-band channel than it is in reality, so that you will introduce a retrieval bias, because you will assign less oxygen absorption to the EPIC measurements and your CTP_top will be lower (or CTH_top higher).

I admit that after convolution with the instrument response function you might be less prone to this, but then I would appreciate also such values in Table 1, together with the same values for the A-band wavelengths.

Author reply: In the updated manuscript, Section 2.3.2 and Figure 2 describes the application of double-k approach based on the fast radiative transfer model. The detailed information about this fast radiative transfer model was shown in the Duan et al. JGR, 2005: "Duan, M., Min, Q. and Li, J.: A fast radiative transfer model for simulating high-resolution absorption bands. Journal of Geophysical Research: Atmospheres, 110(D15), 2005."

The bias in Figures 2 and R2 is from the accuracy of double-k approach itself. In both LBL benchmark simulation and fast radiative transfer model simulation, we already considered the

Rayleigh scattering and aerosol loading. In this study, background aerosol with AOD = 0.08 is used in the radiative transfer calculation.

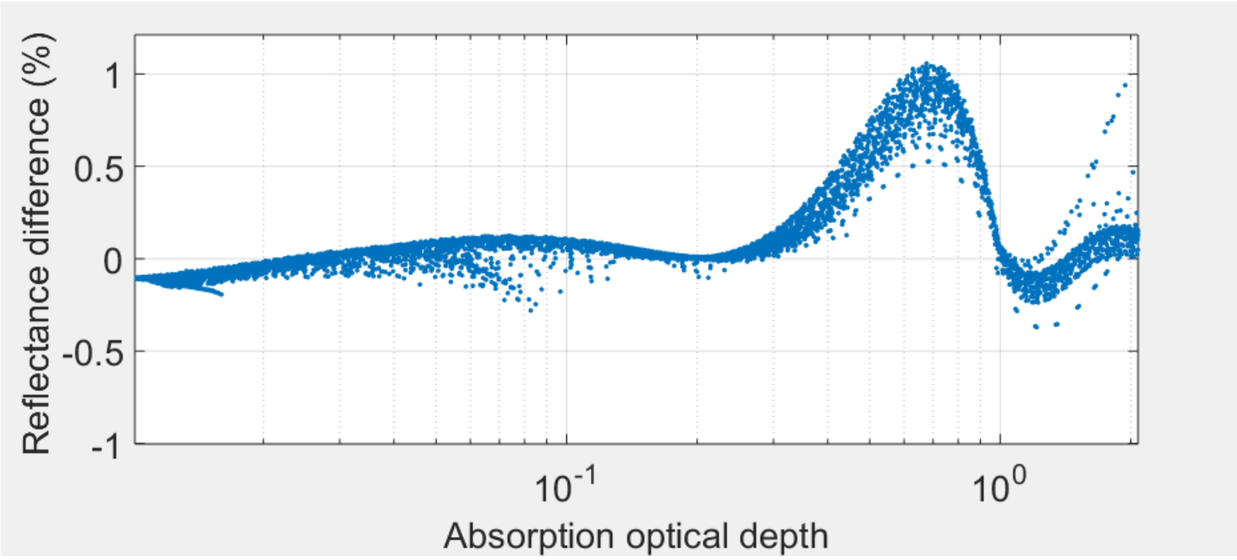


Figure R2. Differences between simulated spectra by the benchmark and fast radiative transfer models as a function of absorption optical depths for a clear day case.

From our point of view, the error of CTP retrieval from radiative transfer calculation should be negligible. When absorption optical depth is small (out of band area), the relative difference is only around 0.1%. Although the relative accuracy of high resolution spectra at oxygen absorption peak positions between fast radiative transfer calculation and LBL calculation is up to 1%, but its effect on the radiation is very small because of the high OD at that wavelength position. After convolution with the instrument response function, the accuracy of the fast radiative transfer model is high, as shown in Table 1. The other thing is that we only used the double-k approach to calculate oxygen A- and B-band absorption channels (764 and 688 nm). For reference bands, we did radiative transfer calculation directly by using narrowband profiles of oxygen absorption optical depth at 679.64 and 779.24 nm.

The retrieval errors of CTP are mainly from other sources, we will discuss them in the replies for the later questions.

In summary:

- please expand Table 1 with results for a Thick Cloud (which optical depth?) – provide also the altitude/pressure of the simulated thin and thick cloud (ensure that you have a representative altitude for the specific cloud: low-level thick cloud and high-level thin cloud) - Specify if the thermodynamic phase of the thin cloud is mixed or ice. Assuming the low-level thick cloud is warm, aka liquid. - Present results for all 4 EPIC channels (680, 688, 764, 779 nm) separately *AFTER* convolution with the EPIC narrowband functions - It is not clear to me what is the last column about. Is the Difference (+0.08%, -0.02%) the average relative difference across the band or only at 688 nm? As such, these numbers are little informative.

Author reply: For EPIC oxygen A-band and B-band reference channels (779 and 680 nm), because their optical depth spectra are smooth and contain no absorption lines, we do not calculate high resolution spectra for them. We do calculations directly by using the narrowband oxygen absorption optical depth profiles at 679.64 and 779.24nm. In the revised manuscript, we expanded Table 1 for both oxygen A and B absorption bands, including results for a thick cloud. The last column shows the cases' relative error between double-k approach and LBL calculation: (DBL_K – LBL)/LBL*100%. In this study, all the radiative transfer calculations are based on the assumption of homogenous liquid water cloud.

The expanded Table 1 and updated manuscript is shown as follows:

"…Therefore, for the simulated narrowband measurements at EPIC oxygen B-band, the relative difference between LBL and double-k approach is much smaller than that of the high resolution spectrum, which is less than 0.1% for clear day. Compared to clear sky situation, the relative difference for cloud situations can be bigger. As shown in Table 1, the relative difference is -0.06% and -0.32% for typical high level optical thin cloud and low-level thick cloud situations, respectively. The comparison of simulated narrowband measurement at EPIC oxygen A-band channel (764 nm) is also shown in Table 1, the relative differences between LBL and double-k approach are -0.06%, 0.21% and 0.23% for clear day, high level thin cloud and low level thick cloud cases, respectively. In general, the accuracy of double-k approach for both oxygen A and B absorption bands is high."

Table 1. Comparison of simulated narrowband measurement at EPIC A- and B-Band channels

Case (SZA=35, surface albedo =0.02)		Line by Line	Double k	Relative Difference
Clear Day	688 nm	0.026963	0.026985	+0.08%
	764 nm	0.013979	0.013970	-0.06%
Thin cloud (COD=2, 8.3-8.5 km, liquid)	688 nm	0.098444	0.098131	-0.32%
	764 nm	0.071359	0.071507	+0.21%
Thick cloud (COD=16, 1.5-2.9 km, liquid)	688 nm	0.396354	0.396117	-0.06%
	764 nm	0.233937	0.234485	+0.23%

P10 L329: You might be correct about the similar behavior of the A-band compared to the b-band. However, the presence of the red edge beyond 690 nm would make your results different for Figure 3-d. The authors suggest to have already such results for then A-band as well, so could you please create a separate Figure with only the dependence on surface albedo with the A and b-band together? This is more informative to the reader in general, as there are several instruments not convering the b-band but solely the A-band.

Author reply: In the simulation, we set a series of surface albedo for both oxygen A-band and B-band. However, when we calculate the ratio of absorption/reference, we assume that the oxygen absorption band and reference band have the same surface albedo. If there is substantial difference of surface albedo between oxygen A-band and B-band due to the red edge, the retrieved CTP based on measurements of oxygen A-band and B-band may have a big difference if the impact of the red edge is not accounted.

We have added a separate Figure (Figure 4) with only the dependence on surface albedo with the A and B-band together. The figure and the related paragraph are shown as follows:

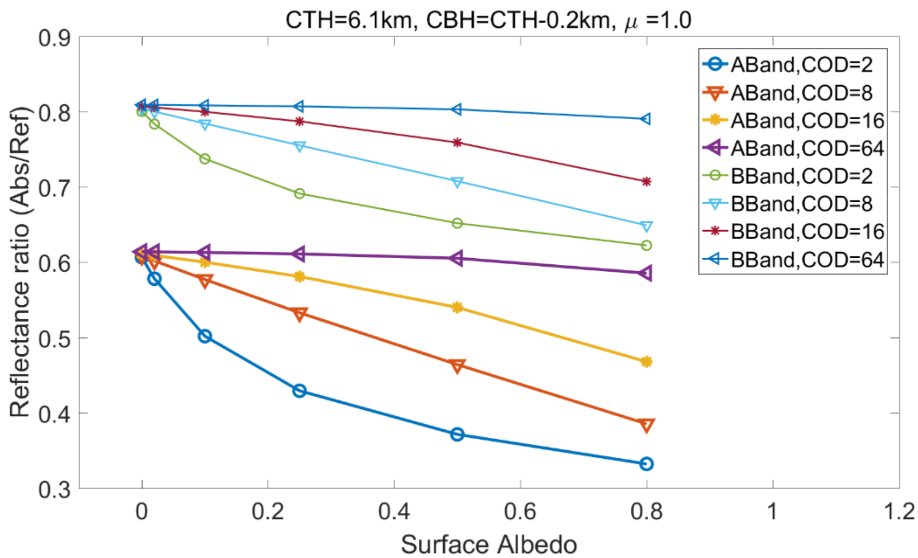


Figure R3 (Figure 4). Ratio of simulated reflectance measurements for EPIC A and B absorption band to reference band with different surface albedo.

"For oxygen A-band, the ratio of upward diffuse at absorption and reference bands shows similar characteristics as for oxygen B-band. Compared to oxygen B-band, under the same atmospheric conditions, the oxygen absorption at A-band is stronger, and the ratio of A-band to its reference band has smaller values (shown in Figure 4). As stated previously, for land area that covered with plants, the surface albedo may change substantially from oxygen B-band to A-band due to the presence of the red edge. Therefore, accurate spectral data of surface albedo for CTP retrieval is vitally important, especially for optically thin clouds."

P11 Section 4.4 "Case studies ..."

This section is missing some important information and is disappointing to read because it lacks a clear structure and explanation of the results is not satisfying. I have several remarks.

Beside some corrections listed in the "Minor Comment" section, I wonder why the authors are introducing Eq. (15) about COT while ending the introducing paragraph with considerations about CTP retrieval.

Author reply: The Eq. (17) (Eq. (15) in the original manuscript) is used to show why we need double-k approach based on the fast radiative transfer model: "We cannot simply calculate narrowband mean optical depth and then calculate the radiation for various atmospheric conditions when simulating EPIC narrowband measurements."

Nevertheless, first, it is not clear where the data for Figure 4 come from. Please add a source repository to enable the replication of your results. It is not clear what L1 data are you processing. So, please give information on the timestamp and the data versioning, reprocessing and so on and guide the reader to the actual source, as not everyone ought to be fluent in EPIC data acquisition and handling.

Author reply: We have added one paragraph to present the data source and also listed the detailed web link information for data downloading in the section Acknowledgements and Data.

"The dataset of DSCOVR EPIC measurements at GMT 00:17:51 on July 25, 2016 is used for the case studies. The reflectance at oxygen A and B bands with related solar zenith and viewing angles are obtained from the EPIC level 1B data; COD information (retrieved from other EPIC channels) is obtained from EPIC level 2 data. The surface albedo data is obtained from Global Ozone Monitoring Experiment 2 (GOME-2) Surface Lambertian-equivalent reflectivity (LER) data. The detailed information of dataset is shown in the acknowledgements and dataset…. "

"**Acknowledgements and Data**

….Dataset of DSCOVR EPIC Level 1B can be found in https://eosweb.larc.nasa.gov/project/dscovr/dscovr_epic_l1b_2; dataset of EPIC Level 2 can be found in https://eosweb.larc.nasa.gov/project/dscovr/dscovr_epic_l2_cloud_01; dataset of surface albedo from GOME can be found in http://temis.nl/surface/gome2_ler/databases/ http://temis.nl/surface/gome2_ler/databases/; dataset of cloud layer data from CALIPSO can be found in https://eosweb.larc.nasa.gov/project/calipso/cal_lid_l2_05kmclay_standard_v4_20."

Second, are the retrievals of Figure 4 for the full EPIC disc? The scatterplots show clustering that must be analyzed and understood. So, I invite the authors to subset L1 radiances after underlying surface reflectance and cloud optical thickness, or latitude or cloud system/regime so that you will be able to geophysically explain the scatterplots. Also, in absence of bias histograms, they must be at least redrawn as heat or occurrence maps with a color coding for the third axis.

Author reply: The retrievals of Figure 5 (Figure 4 in the original paper) is not for the full EPIC disc. In the revised manuscript, "To reduce the impact of the Earth surface, we selected the region located in spatial range of (S75° to N85°, W177° to W175°) for case studies, which is mainly covered by ocean. To constrain the influence of surface albedo and broken clouds, only pixels with total cloud cover (i.e., EPIC Cloud mask = 4), surface albedo less than 0.05, and liquid assumed COD larger than 3 are considered. " To show the statistics of bias, we have added the bias histograms in both Figure 5 and Figure 6 in the revised manuscripts.

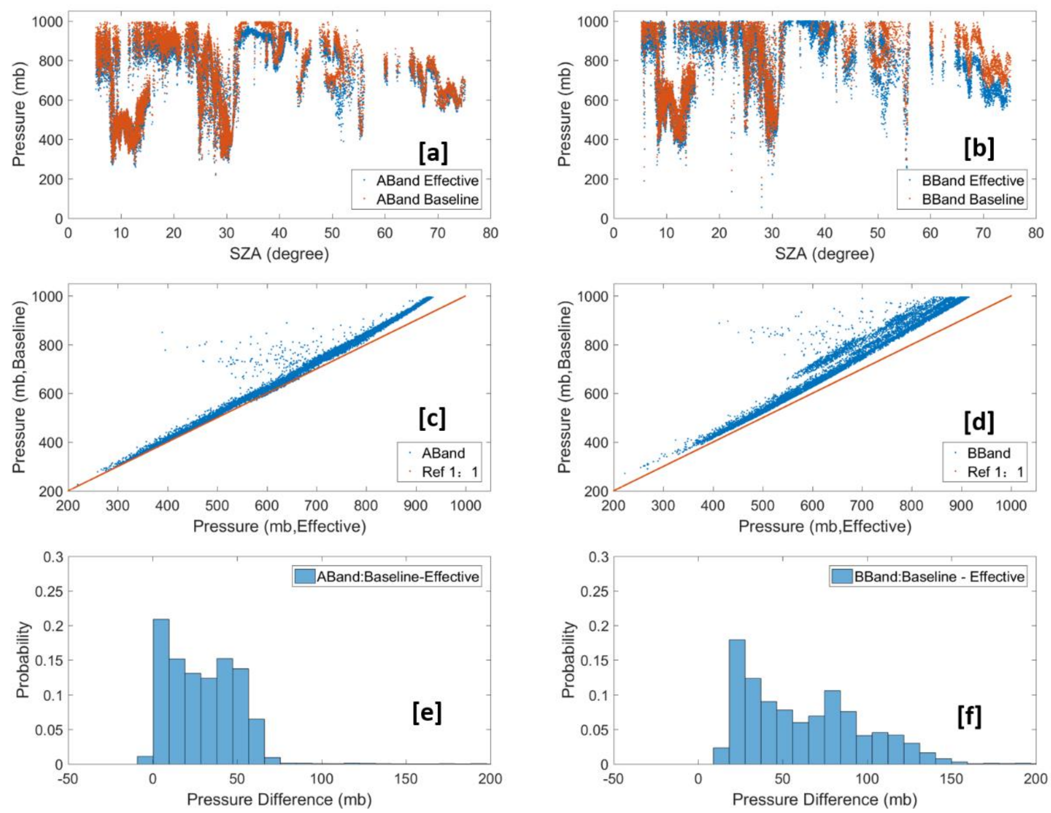
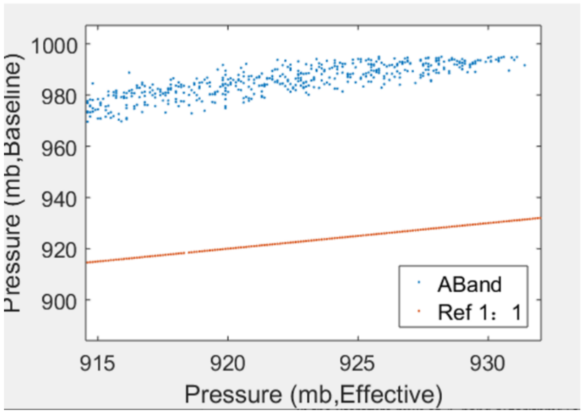


Figure R4 (Figure 5). The comparison of effective CTP (reference from NASA ASDC data) and baseline values from our retrieval algorithm for EPIC A and B bands.

Third, Figure 4: you are comparing an "effective" CTP retrieval (the NASA ASDC L2 record) that does not include photon penetration with your "baseline" CTP method, which does not include photon penetration either. And you still have mean biases for low-level clouds of 100 mb and 150 mb for the A-band and b-band respectively. The apparent "banana" shape, bending toward the ground, might also indicate that you are using different P-T atmospheric profiles, which then impact gaseous extinction. Have you ensured that you are using the same atmosphere of the standard L2?

Author reply: As shown in Figure R5 (expanded plot of Figure R4c and R4d), there are mean biases for low-level clouds of 60 mb and 100 mb for the A-band and B-band, respectively. The difference between our retrieval and the “effective" CTP retrieval (the NASA ASDC L2 record) is not from the difference of P-T atmospheric profiles. We tried different atmospheric profiles (from M1 to M6), this issue always exists. It is from the calculation of absorption optical depth profile (i.e., varying of absorption optical depth with CTP). Our calculation is based on high spectral resolution direct beam calculation directly, which optical depth coefficients are derived by LBLRTM model with HITRAN database. For the “effective” CTP retrieval, the calculation of absorption optical depth profile is based on relatively lower spectral resolution solar spectrum simulation, and it is not based on direct beam calculation directly. Therefore, there exists difference in the absorption optical depth profiles between our retrieval and the “effective" CTP retrieval.



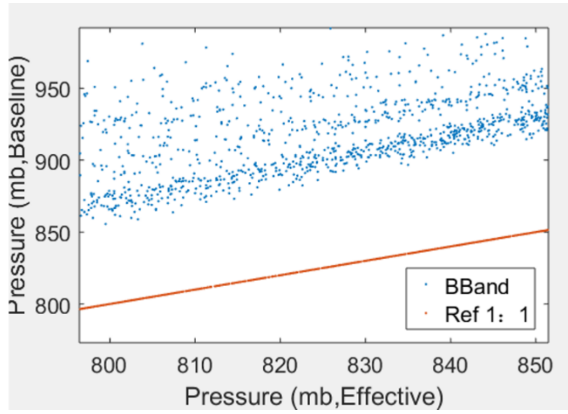


Figure R5. The expanded plot of Figure R4c and R4d.

The detailed information about the calculation of absorption optical depth profile for 'baseline CTP" retrieval is shown as follows:

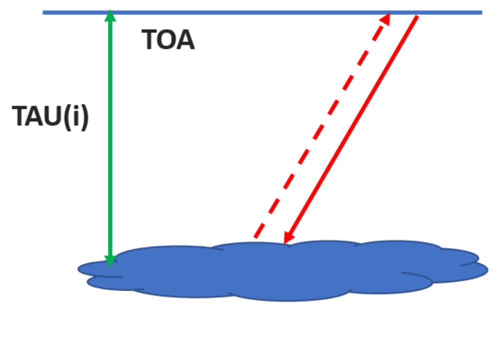


Figure R6. The sketch map of solar direct beam and its mirror reflection from cloud top.

1) Set up a given cloud top height (pressure) and assume that all the incident solar radiation is reflected by the cloud top like a mirror (shown in Figure R6).
2) Calculate high resolution A-band reflected radiation transmission spectrum at TOA line by line based on the equation： TX(i) = exp(-**2***Tau(i)/umu). Here the Tau (i) only includes the absorption optical depth.
3) Calculate the integrated narrowband reflected radiance that received by sensor by multiplying the high resolution spectrum with the related EPIC filter function.
4) Calculate the effective TAU for EPIC A(B)-band based on the simulated integrated radiance.
5) Build a **LUT** for different UMU and cloud top height.
6) Do the 'baseline CTP' retrieval by using EPIC reflectance ratio (Rabs/Rref) and this **LUT.**

Fourth, I hope that the authors would agree with me that the results of Section 4 are still simply a verification of their algorithm and cannot be considered a real validation of their method. Figure 4 compares tow similar methods (as stated by the authors at P11 L335-336) while Figure 5 is simply an internal check of the methods presented in the paper. These results are already known in the literature bulk of A-band algorithms (e.g. by comparison of SACURA, FRESCO, ROCINN, See the TROPOMI S5P Science Verification Report). So, to gain insight in the validity and limitation of your algorithm and to let the reader decide whether your approach is best suited for a cloud type or another (for instance low-level warm or high-level thin cirrus clouds) independent validation is needed and must be carried out against a different CTP derived from coincident retrievals and alternative methods, being this ground-based or space-borne, your choice. But validation is needed.

Author reply: In the revised paper, we have added a subsection (i.e., Subsection 3.2, Validation of the retrieval method) for the validation analysis. We used the cloud layer data from CALISPO as a reference to validate our retrieval algorithm. The detailed result of validation is shown in Figure R6 and Subsection 3.2: "Validation of the retrieval method".

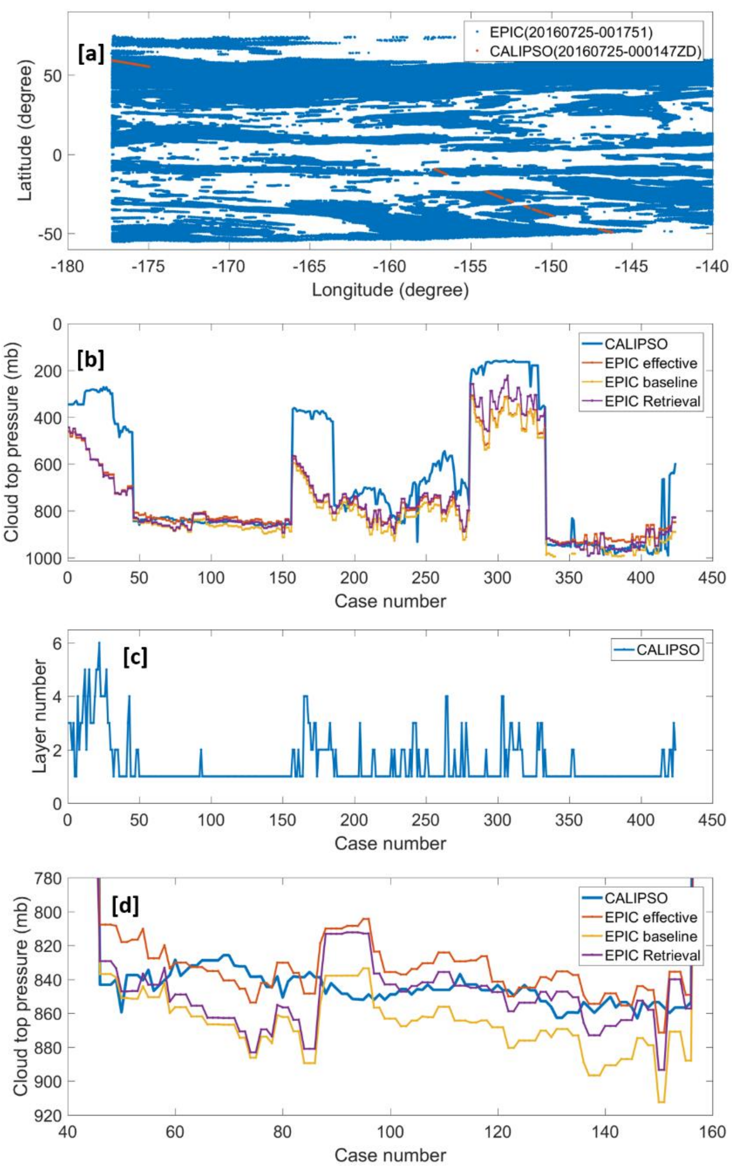


Figure R7. (a) The geolocation match of EPIC measurement at GMT 00:17:51 and CALISPO measurement at GMT 00:01:47 on July 25, 2016; (b) the comparisons of cloud layer top pressure from CALIPSO measurements and the CTPs derived from EPIC measurements; (c) the cloud layer number from CALIPSO measurements; and (d) the expanded view of (b) for some cases under single layer cloud situations.

"For the previously stated case, i.e., DSCOVR EPIC measurements at GMT 00:17:51 on July 25, 2016, we used the cloud layer data from CALIPSO IIR Version 4.2 Level 2 product with 5 km resolution at GMT 00:01:47 on July 25, 2016 as its reference to do validation. To constrain the error from spatial differences between different satellite measurements, we only chose the pixels of EPIC and CALIPSO measurements with a spatial distance of within 0.1º (degree of latitude or longitude) to make comparisons." Through the comparisons, we get the following results: "…under single- layer cloud situations, the CTPs derived from EPIC measurements are close to the CTP from CALISPO; under multi-layer cloud situations, the CTPs derived from EPIC measurements are larger than to the CTP from CALISPO… For these single layer cloud cases (with case number 46 ~ 156), the mean values of CTP of CALIPSO, EPIC effective, EPIC baseline and EPIC retrieval are 846, 834, 866 and 850 mb, respectively. Compared to the CTP from CALIPSO measurements , the EPIC effective and baseline CTPs are 12 mb smaller or 20 mb larger, respectively; the EPIC retrieval with photon penetration consideration is only 4 mb larger. This shows that our method for the CTP retrieval is valid and accurate under single layer cloud situations with COD > 3 and low surface albedo. Under multi-level cloud situations, the high-level clouds are often thin clouds, which can be detected by CALIPSO but hard to be derived by our retrieval method. It is because that the EPIC retrieved CTP mainly shows the pressure of cloud layer that reflects the major part of incident sun light."

Fifth, can the authors provide the reasoning behind the choice of their "statistical approach" to estimate cloud geometrical/pressure thickness? Why are you calling it a statistical approach, I would rather call it assumption? Surely this assumption is based on evidence, likely drawn by references or assessment studies. So, please make the derivation of your assumption about this approach explicit. Moreover, no details on the physics behind are given. Where are all the terms of the expression (i.e. the multiplicative factor 2.5, the additive +26) coming from? Expected limitations and range of applicability of this assumption? Any relationship with/dependence on cloud liquid water content and/or cloud type? One pertinent reference on my own I can come up with is Carbajal Henken et al. AMT, 2015 where CTP is related to pressure thickness and optical depth. But the same result has been obtained also by Rozanov and Kokhanovsky, JGR 2004 and Lelli et al, AMT, 2012 and ACP 2016 (see Appendix). It will be interesting to augment this bulk of literature with the references provided by the authors.

Author reply: For the issue about "statistical approach to estimate cloud geometrical/pressure thickness", it can be seen as an assumption. We have discussed this issue in the previous replies in details.

Finally, Figure 5. Fig. 5-a and 5-b extend the results of Fig.4-c and Fig.4-d, correct? You are using the same scenes of the NASA ACDC L2 record and you compare your baseline-CTP with the retrieved-CTP? Could you please elaborate why is the B-band closer to the A-band retrieval when photon penetration in the cloud is allowed? The sentence at P13 L378 ("This indicates, as expected, more photon penetration correction for B-band than A-band") reads a gap filler and sounds like the authors want to get away with this without further investigation. There is a reason why the B-band is not customarily used for calibration of surface pressure. Some of the co-authors are surely aware of this effect.

Author reply: Figure 5 (Figure 4 in the original paper) only showed the analyses of baseline-CTP retrieval, which is not related to the analytical method. The Figure 5 shows that the optical depth profiles that we used for retrieval is different from the optical depth profiles used by NASA ASDC L2 data processing package. Figure 6 (Figure 5 in the original paper) shows the results related the analytic retrieval method. We compared our own baseline-CTP and the retrieved-CTP to show that the impact of photon penetration on the CTP retrieval.

Because the oxygen absorption capability at B-band is relative weaker than at A-band, therefore the impact of photon penetration on CTP retrieval at B-band is stronger. The difference between baseline-CTP at B-band and real CTP should be larger than that at A-Band. With considering the photon penetration, retrieved CTP decreased by more at B-band than at A-band (shown in Figure 6).

Section 4.5 "Retrieval of global observation"

It is not clear if the same filtering (cloud cover = 1, cloud optical thickness _ 3, surface albedo < 0.25) is applied for the generation of the RGB snapshot of Fig.6-a. Also in view of Fig.6-d, COT: based on the visual inspection of the patterns, the cloud systems are quite different between the two maps, which are in turn also different from the CTP maps. The patterns are, in my opinion, quite different: the Nothern Pacific system is captured neither in the COT (Fig.6-d) nor in the CTP (Figs.6-b,c,e,f), being the B-band overall shallower/fainter than the A-band. This could point to the choice of grounding all filtered NANs (not-a-number) to 1013 mb, making them valid retrievals in the color scale, albeit representing a fake surface pressure. I would then make this point grey or white, in all Figs.6 b to f and leaving Fig.6-a untouched.

Author reply: In the revised paper, Figure 6 has been updated by Figure 8. Figure 8a is an RGB snapshot downloaded from website of NASA ASDC. We did not apply any filtering to the RGB snapshot. COT data in Figure 8b is directly from the NASA ASDC L2 data file. In the revised paper, we added another figure (Figure 8c) to show the A-band effective CTP; data is also from NASA ASDC L2. We have updated all the Figures except Figure 6a by plotting the invalid data with white color as suggested. According to the new figures, the cloud areas indicated by COD and A-band effective CTP are consistent with the RGB image in Figure 8a. We have updated the related comments in the revised paper.

It is not clear to my why the authors are using the L2 COT from NASA ASDC and not their own as specified by Eq. (15). If the calculation of COT in this paper differs (or it is the same) from the one in Yang et al. (2013) this must be stated at the beginning of Section 4.4. Otherwise the reader cannot judge in any way the soundness of the sentence in P13-14 L399-402 about the error propagation of COT into CTP.

Author reply: We do not have own COT data. The Eq. (15) is used to present the argument: For a wavelength range with many absorption lines, we cannot use the average value of the absorption optical depth spectrum to calculate the narrowband radiance directly. We need to calculate the radiance spectrum based on the optical depth spectrum, and then integrate the radiance spectrum to calculate the narrowband radiance. At the same time, the Eq. (15) is not related to the calculation of cloud optical depth. Therefore, we use the L2 COT data from NASA ASDC for our retrieval.

To conclude, this section lacks some explanation about the patterns we see in the disc. I understand that the Pacific is a favorable geophysical scene to analyze, due to the lack of difficult reflective ground. However, the authors are capturing a wealth of cloud systems: deep convective clouds within the tropical belt, subsidence clouds in the trade wind belts, near-polar clouds at high latitudes, low-level warm cloud decks, even some cirrus clouds may slip through a COT filter of 3 (perhaps). Each of this cloud type can be categorized after its average cloud optical thickness. Please, introduce COT in your error analysis.

And also create difference maps centered on 0 mb with a divergent color palette for Fig.6c-Fig.6f and Fig.6c-NASA_L2_ASDC.

Author reply: In the revised paper, we have created two more figures (i.e., Figures 8f and 8i) as suggested. We have updated and added some comments, such as: "…Figure 8c shows the A-band effective CTP (NASA ASDC L2 data), where the white areas indicate clear sky or no valid values, warm (brown) and cold (blue) color areas indicate high-level and low-level clouds, respectively. According to the A-band effective CTP, the high-level clouds are dominant in the equatorial area, and the low-level clouds play a major role in the cloud systems in the Northern Pacific area… The difference of A-band retrieved CTP and A-band effective CTP is shown in Figure 8d. The A-band retrieved CTP is overall smaller than A-band effective CTP, which difference is within 100 mb. The highlighted (brown) areas are located in the high level clouds areas or large COD areas. This indicates that the complexity of cloud system has significant impact on the CTP retrieval…"

In the subsection 3.2, i.e., Validation of the retrieval method, we have obtained some results: under single-layer cloud situations, the CTPs derived from EPIC A-band measurements have good agreement with the CTP from CALIPSO measurements; under multiple-layer cloud situations, the CTPs derived from EPIC measurements may be larger than the CTPs of high level thin-clouds due to the effect of photon penetration. Therefore, in the global range, for the large scale low-level stratus clouds, the retrieved CTPs from EPIC A-band measurements should agree well with the actual value of CTPs, but for the complex cloud system with multiple-layer clouds, the CTPs derived from EPIC A-band measurements may be larger than the CTPs of high level thin-clouds.

P14 L410 Conclusions.

- There is no Yuekui et al. 2012 in the bibliography. Please check.

Author reply: We have changed it to Yang et al. (2019).

- Here the authors need not just to summarize what they have done but also discuss in

a compact way the results and highlight limitations of their method and future developments.

Author reply: We have updated the summary and added one more paragraph in the revised manuscript:

"…The cloud layer top pressure from CALIPSO measurements is used as a reference to validate the CTP derived from EPIC measurement. Under single-layer cloud situations, the retrieved CTPs for oxygen A-band agree well with the CTPs from CALIPSO, which mean difference is within 5 mb in the case study. Under multiple-layer cloud situations, the CTPs derived from EPIC measurements may be larger than the CTPs of high level thin-clouds due to the effect of photon penetration.

Currently, this analytical transfer model method can only retrieve CTP, and it still needs cloud pressure thickness as an input parameter. However, in the satellite observations, both CTP and cloud pressure thickness are unknown. The estimation or assumption of cloud pressure thickness will bring in extra error in CTP retrieval. In the near future, we plan to address this issue. "

*** Minor comments

P1 L15: was -> is

Author reply: We have revised it as suggested.

P9 Figure 2: Please, define in the caption how the difference in reflectance is defined.

Author reply: We have added the definition of the difference in reflectance into the figure caption as follows: "…Here SZA and view angle =35º, surface albedo = 0.02, aerosol optical depth = 0.08, and reflectance difference (%) = 100*((double-k) – LBL)/LBL."

P10 L299: "sensibility of every variant"? You mean "sensitivity to every variable"?

Author reply: We have revised it as suggested.

P10 Figure 3: in the caption please specify that "umu" is cosine of SZA.

Author reply: We have updated Figure 3 and added the related definition into the figure caption as follows:

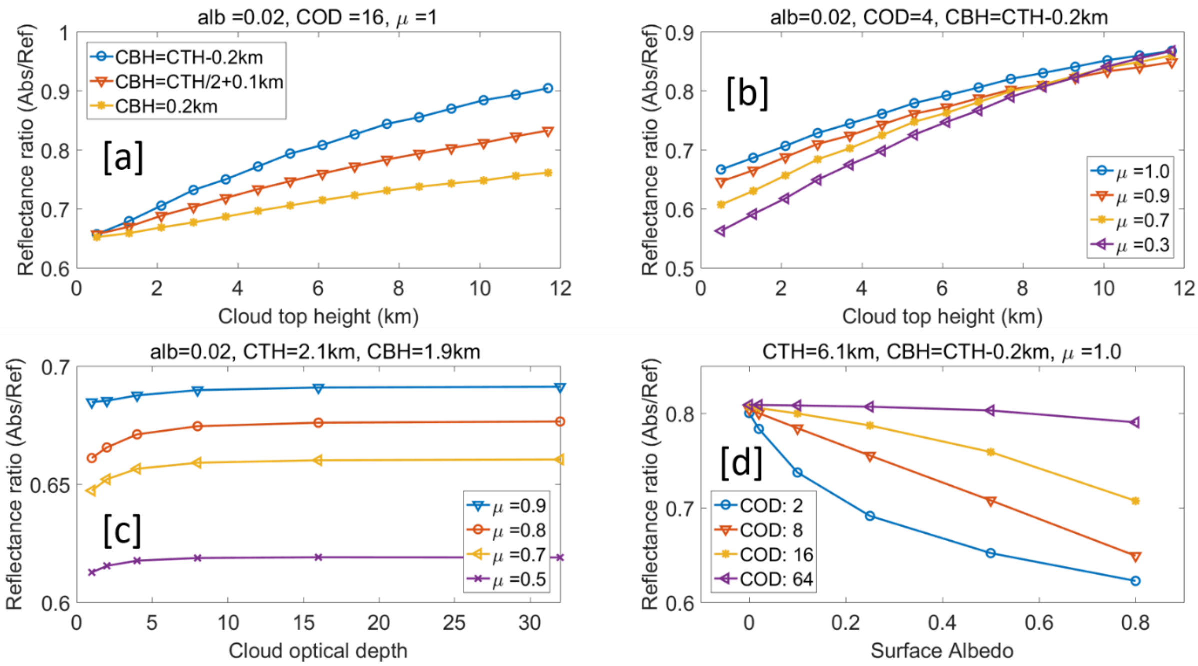


Figure 3. Ratio of simulated reflectance measurements for EPIC B-band to B-band reference with different surface albedo (alb), COD, μ (cosine of solar zenith angle), cloud top height (CTH) and cloud bottom height (CBH).

P10 L309: "ratio of upward diffuse ... ", missing a word, perhaps radiance or radiation?

Author reply: We have revised it as “ratio of upward diffuse radiance”.

P10 L318: please refrain from subjective statements such as "This is easy to understand".

Author reply: We have revised it as “This can be understood as”

P10 L327: you mean "thick" cloud and not "heavy" cloud?

Author reply: We have changed the “heavy” to “thick” as suggested.

P11 L338: if the baseline-CTP mothod is adopted, then in-cloud penetration is not "ignorable" but "ignored" instead. "Ignorable" suggests the existence of an option to be chosen, such that the method still enables the calculation of in-cloud penetration, but the authors choose otherwise. "Ignored" implies that the method offers no option other than those provided. So, "ignored" is more rigorous and exact.

Author reply: We have changed the “ignorable” to “ignored” as suggested.

Section 4.4, Figures 4 and 5: control axis labels. "Pressure" not "Pressue".

Author reply: We revised the axis labels in the revised manuscript.

P11 L339: "light reached cloud top is assumed". missing "that"

Author reply: We have added "that" in the revised manuscript.

P12 L371: what do you mean here with the word "interaction"?

Author reply: We have deleted the word "interaction" in the revised manuscript.

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Carbajal Henken, C. K., Doppler, L., Lindstrot, R., Preusker, R., and Fischer, J.: Exploiting the sensitivity of two satellite cloud height retrievals to cloud vertical distribution, Atmos. Meas. Tech., 8, 3419–3431, https://doi.org/10.5194/amt-8-3419-2015, 2015.

Author reply: Thank you very much for listing all the above references! We have cited them in the revised paper.

We thank the Reviewers for their very thorough and constructive comments, which have helped to improve the quality of this paper. Below are our responses to their comments. The response (e.g., blue) follows each comment.

Comments from the editors and reviewers:

This paper introduces a method to retrieve cloud top heights from measurements in the wavelength range ~680nm to ~780nm in and next to the oxygen A and B absorption bands. Measurements are performed by the EPIC sensor which is operated on a satellite near the first Sun-Earth Lagrange point so that scattering angles are always 165º or larger.

I agree with each point raised by the first reviewer. While the science is probably sound as far as can be judged from the current manuscript, the manuscript requires major revisions and a further round of review before it might be published as a final paper.

Besides some language issues, the description should be improved, e.g. not all steps in section 3.2 can be followed. Section 4 could be split in two parts, since the first part is more about method description while the second part shows the results. Maybe

Sect. 2 + 3 + the first half of Sect. 4 could be merged into one section (called 'Theory and methods' or just 'Methods') with several subsections. A discussion of the results is missing. The conclusion section currently is more like a summary. A few minor remarks:

Author reply: Thank you very much for your comments, we have revised the structure of the paper as suggested : The original sections 2, 3 and half of section 4 have been merged into one section "Theory and methods", the other half of section 4 is categorized into another section "Application and validation of the CTP retrieval method".

- Line 14: " analytic transfer model ": Do you mean your retrieval? In my view, even if it is a relatively simple retrieval and the term 'model' may not be completely wrong it should be called retrieval (or inversion or maybe 'inverse model' or 'retrieval using a analytic transfer model' or similar) because at least some readers will connect the term 'model' more with a forward model than with a retrieval.

Author reply: We have revised it to "An analytic transfer inverse model" as suggested. We also replaced the "analytic transfer model" by "analytic transfer inverse model" in all other places in the paper.

- Line 22: "a one-hundred-fold time reduction": Which time is reduced? (Computation time I guess) Compared to what? (line-by-line calculations?)

Author reply: We have revised this sentence as follows: "…To simulate the EPIC measurements, a program package using the double-*k* approach was developed. Compared to line-by-line calculation, this approach can calculate high-accuracy results with a one-hundred-fold computation time reduction.…"

- Line 36: The spatial resolution of the sensor could be mention here. Also the scattering angle range (>=165_) could be mentioned somewhere.

Author reply: We have revised as suggested: "…One of the Earthward instruments is the Earth Polychromatic Imaging Camera (EPIC) sensor, which can take images of the Earth with spatial resolution of 10 km at nadir. The EPIC continuously monitors the entire sunlit Earth for backscatter, with a nearly constant scattering angle between 168.5º and 175.5º, from sunrise to sunset with 10 narrowband filters: 317, 325, 340, 388, 443, 552, 680, 688, 764 and 779 nm (Marshak et al., 2018)…"

- Figure 1 caption: The model should be mentioned here. Currently it is mentioned only later in the text. Is the figure for 1013hPa? Is it only for O2 or for all atmospheric constituents?

Author reply: We have revised the Figure 1 caption as suggested:

"**Figure 1:** High resolution calculated absorption optical depth spectrum at oxygen A-band (a) and B-band (b) with DSCOVR EPIC oxygen A and B bands in-band and reference filters. Here the absorption optical depth spectrum is calculated by LBLRTM model with HITRAN 2016 database for the U.S. standard atmosphere."

This figure is for U.S. standard atmosphere, which surface pressure is 1013 hPa. It is for all atmospheric constituents.

- Line 122: 'we are trying to develop' could be replaced by 'we develop'.

Author reply: We have revised as suggested.

- Line 134: 'outer space' could be replaced by 'TOA'.

Author reply: We have revised as suggested.

- Line 144: 'airmass and aerosol that located above or below cloud': also inside a cloud Rayleigh scattering and extinction by aerosols can happen.

Author reply: We have revised it as follows: "… For solar radiation at oxygen A-band and its reference band, they are also attenuated by airmass and aerosol through Rayleigh scattering and aerosol extinction…"

- Line 152: 'between solar and satellite sensors': You mean 'between Sun and satellite sensor'?

Author reply: Yes, we have revised as suggested.

- Line 154: 'layerd' should be 'layered'.

Author reply: We have revised as suggested.

- Line 284: ’and hard to tell directly’ should be removed.

Author reply: We have revised as suggested.

- Line 371: ’decrease’ should be ’increase’ if I understand correctly.

Author reply: Here the “retrieved CTP (with considering cloud penetration)” is smaller than the “baseline CTP (without considering cloud penetration)”. Hence, we say “A decrease in retrieved CTP will …” in this sentence.

Cloud top pressure retrieval with DSCOVR-EPIC oxygen A and B bands observation

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Abstract

An analytic transfer inverse model for Earth Polychromatic Imaging Camera (EPIC) observation ~~was~~ is proposed to retrieve the cloud top pressure (CTP) with considering in-cloud photon penetration. In this model, an analytic equation was developed to represent the reflection at top of atmosphere (TOA) from above cloud, in-cloud, and below-cloud. The coefficients of this analytic equation can be derived from a series of EPIC simulations under different atmospheric conditions using a non-linear regression algorithm. With estimated cloud pressure thickness, the CTP can be retrieved from EPIC observation data by solving the analytic equation. To simulate the EPIC measurements, a program package using the double-*k* approach was developed. Compared to line-by-line calculation, ~~which~~ this approach can calculate high-accuracy results with a one-hundred-fold computation time reduction. During the retrieval processes, two kinds of retrieval results, i.e., baseline CTP and retrieved CTP, are provided. The baseline CTP is derived without considering in-cloud photon penetration, and the retrieved CTP is derived by solving the analytic equation, taking into consideration the in-cloud and below-cloud interactions. The retrieved CTP for the oxygen A and B bands are smaller than their related baseline CTP. At the same time, both baseline CTP and retrieved CTP at the oxygen B-band are ~~obviously~~ larger than those at the oxygen A-band. Compared to the difference of baseline CTP between the B-band and A-band, the difference of retrieved CTP between these two bands is generally reduced. Out of around 10000 cases, in retrieved CTP between A- and B-bands we found an average bias of 93 mb with standard deviation of 81 mb. The cloud layer top pressure from Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations measurements is used to do validation. Under single-layer cloud situations, the retrieved CTPs for the oxygen A-band agree well with the CTPs from CALIPSO, which mean difference is within 5 mb in the case study. Under multiple-layer cloud situations, the CTPs derived from EPIC measurements may be larger than the CTPs of high level thin-clouds due to the effect of photon penetration.

1. Introduction

The Deep-Space Climate Observatory (DSCOVR) satellite is an observation platform orbiting within the first Sun-Earth Lagrange point (L1), 1.5 million km from the Earth, carrying a suite of instruments oriented both Earthward and sunward. One of the Earthward instruments is the Earth Polychromatic Imaging Camera (EPIC) sensor, which can take images of the Earth with spatial resolution of 10 km at nadir. The EPIC continuously monitors the entire sunlit Earth for backscatter, with a nearly constant scattering angle between 168.5° and 175.5°, from sunrise to sunset with 10 narrowband filters: 317, 325, 340, 388, 443, 552, 680, 688, 764 and 779 nm (Marshak et al., 2018). Of the 10 narrow-band channels, there are two oxygen absorption and reference pairs, 764nm versus 779.5nm and 680nm versus 687.75nm, for oxygen A and B bands. The cloud top pressure (CTP) or cloud top height (CTH) is an important cloud property for climate and weather studies. Based on differential oxygen absorption, both EPIC oxygen A-band and B-band pairs can be used to retrieve CTP. It is worth noting that although CTP and CTH reference the same characteristic of clouds, the conversion between the two depends on the~~ir~~ related atmospheric profile~~s~~.

Although the theory of using oxygen absorption bands to retrieve CTP was proposed decades ago (Yamamoto and Wark, 1961), it is still very challenging to do the retrieval accurately due to the complicated in-cloud penetration effect (Yang et al., 2019, 2013; Davis et al., 2018a, 2018b; Richardson and Stephens, 2018; Loyola et al., 2018; Lelli et al., 2014, 2012; Schuessler et al., 2013; Rozanov and Kokhanovsky, 2004; Kokhanovsky and Rozanov, 2004; Kuze and Chance, 1994; O'brien and Mitchell, 1992; Fischer and Grassl, 1991; and etc.). To estimate the CTP from satellite measurements, ~~Many~~ many approaches ~~are~~ have been designed to retrieve clouds' effective top pressures without considering ~~their~~ in-cloud photon penetration. These approaches did not consider light penetrating cloud, ~~and~~ therefore the derived CTH is lower than the cloud top, ~~derive~~ and the effective top pressures is higher than CTP. In the meantime, to improve the retrieval accuracy of CTP, various techniques have been applied to the retrieval methods with in-cloud photon penetration. For example, Kokhanovsky and Rozanov (2004) proposed a simple semi-analytical model for calculation of the top-of-atmosphere (TOA) reflectance of an underlying surface-atmosphere system, accounting both for aerosol and cloud scattering. Based on the work of Kokhanovsky and Rozanov (2004), Rozanov and Kokhanovsky (2004) developed an asymptotic algorithm for the CTH and the geometrical thickness determination using measurements of the cloud reflection function. This retrieval method was applied by Lelli et al. (2012, 2014) to derive CTH using measurements from GOME instrument on board the ESA ERS-2 space platform.

Currently, based on the measurements of DSCOVR EPIC sensor, the Atmospheric Science Data Center (ASDC) at National Aeronautics and Space Administration (NASA) Langley Research Center archives both calibrated EPIC reflectance ratio data and processed Level 2 cloud retrieval products, including cloud cover, cloud optical depth (COD), cloud effective top pressure at oxygen A and B bands (Yang et al., 2019). By using EPIC reflectance ratio data at oxygen A-band and B-band absorption to reference channels, Yang et al (2013) developed a method to retrieve CTH and cloud geometrical thickness simultaneously for fully cloudy scene over ocean surface. First their method calculates cloud centroid heights for both A- and B-band channels using the ratios between the reflectance of the absorption and reference channels, then derives the CTH and the cloud geometrical thickness from the two dimensional look up tables that relate the sum and the difference between the retrieved centroid heights for A- and B-bands to the CTH and the cloud geometrical thickness. The difference in the O_2 A- and B-band cloud centroid heights is resulted from the different penetration depths of the two bands. Compared to the cloud height variability, the penetration depth differences are much smaller and the retrieval accuracy from this method can be affected by the instrument noise (Davis et al. 2018a, b).

In this paper, to address the issue of in-cloud penetration, we proposed an analytic method to retrieve the CTP by using DSCOVR EPIC oxygen A- and B-band observation. This analytical method adopted ideas of the semi-analytical model (Kokhanovsky and Rozanov, 2004; Rozanov and Kokhanovsky, 2004), and developed a quadratic EPIC analytic radiative transfer equation to analyze the radiative transfer in oxygen A- and B-band channels. The structure of this paper is as follows: section 2 describes the theory and methods, which includes several subsections, i.e., the introduction of ~~absorption optical depth spectrum at oxygen A and B bands with their related~~ DSCOVR EPIC oxygen A and B bands filters, the theory of CTP retrieval based on EPIC oxygen A- and B- band observation, and the detailed retrieval algorithm; section 3 describes the application and validation of the CTP retrieval method, which also includes several subsections, i.e., case studies of CTP retrieval, validation of the retrieval method, and retrieval of global observation;~~states the theory of CTP retrieval based on EPIC oxygen A-band and B-band observation, section 4 describes the retrieval algorithms in detail with case studies and examples of global observation data retrieval,~~ and section ~~5~~ 4 states the conclusions of this study.

2. Theory and methods

2.1 DSCOVR EPIC oxygen A and B bands filters

EPIC filters at 764 nm and 779 nm cover the oxygen A-band absorption and reference bands, respectively (Figure 1a). The high resolution absorption optical depth spectrum at oxygen A-band and B-band is calculated by Line-By-Line Radiative Transfer Model (LBLRTM, Clough et al., 2005) with HITRAN 2016 database (Gordon et al., 2017) for the U.S. standard atmosphere. In this wavelength range, the O3 absorption is very weak (O3 optical depth < 0.003) and there are no other gas absorptions. The background aerosol and Rayleigh scattering optical depth vary smoothly within the A-band range; the differences between in-band and reference band are negligible at nominal EPIC response functions. EPIC filters at 688 nm and 680 nm cover the oxygen B-band absorption and reference band, respectively (Figure 1b). Compared to the oxygen A-band, O3 absorption is slightly stronger in the oxygen B-band range, with an O3 optical depth around 0.01. Any water vapor absorption in the B-band range is negligible. In the standard atmospheric model, from the oxygen B-band reference band to the absorption band, the O3 absorption and Rayleigh scattering optical depth decreased by approximately 0.002 and 0.002, respectively. This may have some impacts on the CTP retrieval from the oxygen B-band (more discussion in the later sections). It is worth noting that for EPIC measurements at both oxygen A- and B-bands, the surface influence cannot be ignored~~is non-ignorable~~. For examples, in the snow or ice covered area the surface albedo is high; in the plants covered area, the surface albedo changes substantially between oxygen A-band and B-band due to the impact of spectral red-edge (Seager et al., 2005).

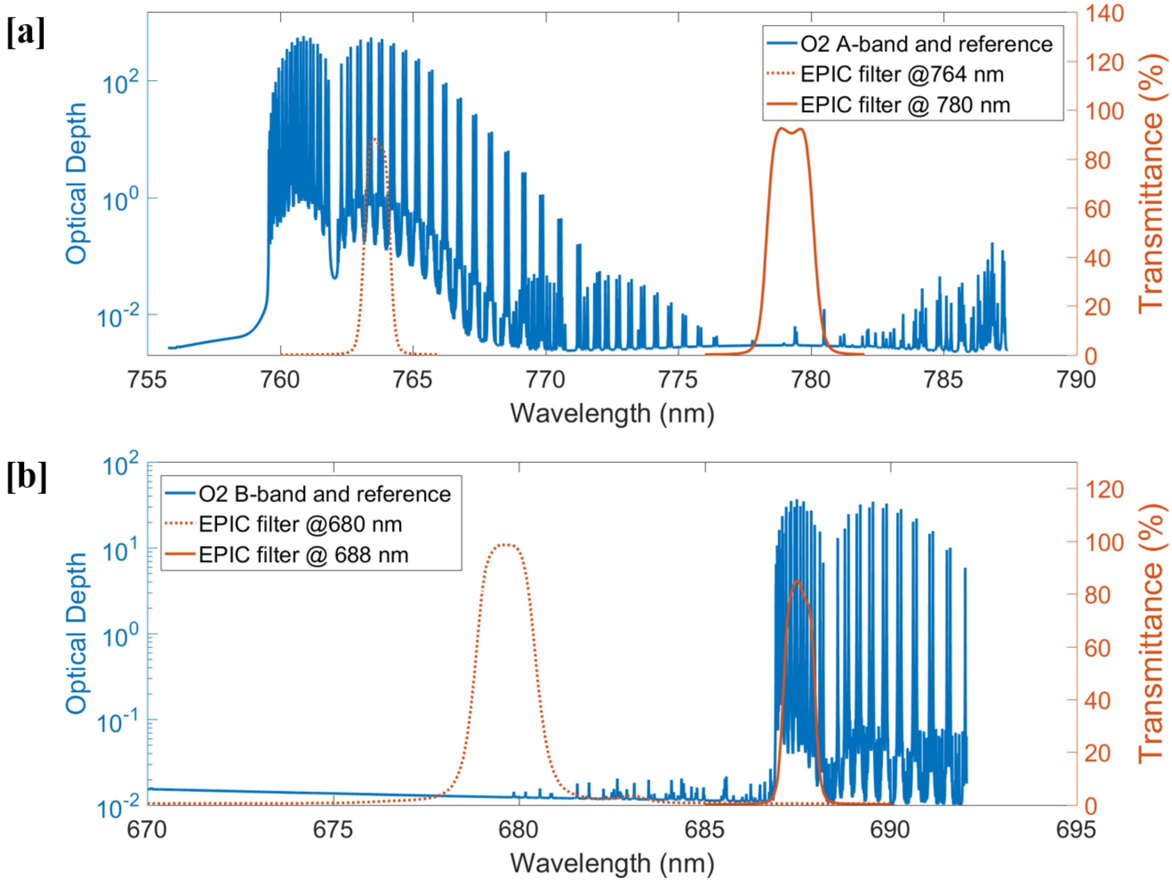


Figure 1: High resolution calculated absorption optical depth spectrum at oxygen A-band (a) and B-band (b) with DSCOVR EPIC oxygen A and B bands in-band and reference filters. Here the absorption optical depth spectrum is calculated by LBLRTM model with HITRAN 2016 database for the U.S. standard atmosphere.

In general, if we use the pair of oxygen A and B absorption and reference bands together, the impact of other absorption lines, background Rayleigh scattering, and aerosol optical depth are very limited. At the same time, as a well-mixed major atmospheric component, the vertical distribution of oxygen in the atmosphere is very stable under varying atmospheric conditions. Thus, we can use the ratio of reflected radiance (or reflectance) at the top of atmosphere (TOA) of oxygen absorption and reference bands (i.e., R_{764} and R_{779} , R_{688} and R_{680}) to study the photon path length distribution and derive the cloud information. Also, compared to any specific EPIC oxygen absorption bands (i.e., R_{764} and R_{688}), the ratios of absorption/ to reference channels (i.e., R_{764}/R_{779} and R_{688}/R_{680}) are less impacted by the instrument calibration and other measurement error. This can be explained by the following reasons: Firstly, the EPIC measurements at oxygen A and B absorption and reference bands share same sensor and optical system, when calculating the ratios of them, some preprocessing calibration errors can be reduced. Secondly, to calculate R_{764} and R_{688}, the ratio of lunar reflectance at neighboring channels (i.e.,$F(764{,}779)$ and $F(688{,}680)$) and the calibration factors of oxygen A and B reference bands (i.e., K_{779} and K_{680}) are used (Geogdzhayev and Marshak, 2018; Marshak et al., 2018). Therefore, the accuracy of R_{764} and R_{688} is determined by the stability of $F(764{,}779)$

and $F(688,680)$ and the accuracy of K_{779} and K_{680} together. But the accuracy of ~~ratios of~~ absorption~~/~~ to reference ratios is only determined by the stability of $F(764,779)$ and $F(688,680)$.

2.2 Theory of CTP retrieval based on EPIC oxygen A- and B- band observation

In our study, we tried two methods to retrieve the CTP based on EPIC oxygen A-band and B-band measurements: (1) Build a lookup table (LUT) for various atmospheric conditions and do the retrieval by searching the LUT; (2) Develop an analytic transfer inverse model for EPIC observations and calculate the related coefficients based on a series of simulated values, then use this analytic transfer inverse model to retrieve the CTP. In this paper, we mainly focus on the second method.

~~3~~2.2.1 Method 1: LUT based approach

One commonly used method of retrieval for satellite observation is through the building and usage of LUTs (Loyola et al., 2018, Gastellu-Etchegorry and Esteve, 2003). LUT based approach can be fast because the most computationally expensive part of the inversion procedure is completed before the retrieval itself. For DSCOVR EPIC observations, we can build ~~a~~ LUTs by simulating ~~the~~ EPIC measurements under various atmospheric conditions, such as different surface albedo, solar zenith and viewing angles, ~~cloud optical depth~~COD, CTP, and cloud pressure thickness. Comparing the related simulated reflectance at the oxygen absorption and reference bands, we can obtain two LUTs for reflectance ratios of absorption/reference at EPIC oxygen A-band and B-band respectively, which can be used for the CTP retrieval. The detailed information of simulated reflectance ratio of absorption/reference is stated in Section 2.3.3.

During the retrieval process, the EPIC measurements (e.g., reflectance at oxygen A and B bands) with related solar zenith and viewing angles can be obtained from the EPIC level 1B data; ~~cloud optical depth~~COD information (retrieved from other EPIC channels) can be obtained from EPIC level 2 data. At the same time, we can get surface albedo from Global Ozone Monitoring Experiment 2 (GOME-2) Surface Lambertian-equivalent reflectivity (LER) data (Tilstra et al., 2017). At this point the CTP and cloud pressure thickness are the only unknown variables. The cloud pressure thickness or the cloud vertical distribution has substantial impact on the accuracy of the CTP retrievals (Carbajal Henken et al., 2015; Fischer and Grassl, 1991; Rozanov and Kokhanovsky, 2004; Preusker and Lindstrot, 2009). In this study, the cloud pressure thickness is used as an input parameter to retrieve the CTP. However, no related accurate cloud pressure thickness is provided by other satellite sensors now. To constrain the error ~~of~~from the estimation of cloud pressure thickness, we related it to the cloud optical thickness. It is reasonable because clouds with higher optical thickness normally have higher values of pressure thickness. To explore the correlation between cloud pressure thickness and cloud optical thickness, we use the related cloud data from Modern-Era Retrospective analysis for Research and Applications Version 2 (MERRA-2, Gelaro et al., 2017), which is a NASA atmospheric reanalysis for the satellite era using the Goddard Earth Observing System Model Version 5 (GEOS-5) with Atmospheric Data Assimilation System (ADAS). Based on statistical analysis of one year's single-layer liquid water clouds over an oceanic region (S23.20, W170.86, S2.11, W144.14) in

2017, we can get an equation for cloud pressure thickness approximation, i.e., cloud pressure thickness (mb) = 2.5* COD + 23. The derived correlation coefficients ~~is~~are dependent on the case region and time selections. ~~In the meantime, d~~Due to the complexity of cloud vertical distribution~~ in the atmosphere~~, whatever the accuracy of the correlation coefficients is, the estimation will certainly bring in error. ~~Cloud pressure thickness can be estimated with cloud optical thickness using statistical rules.~~

With an estimated cloud pressure thickness, ~~A~~a multi-variable LUT searching method can then be used to interpolate and obtain the CTP. It is worth noting that the reflectance ratio of absorption/reference can be seen as a function of surface albedo, solar zenith and viewing angles, COD, CTP, and cloud pressure thickness. ~~certain~~ Some atmospheric variables will have a non-linear effect on the reflectance ratio. For example, the reflectance ratio is more sensitive to the variation of COD when COD is small. Overall, the reflectance ratio varies monotonically and smoothly with these variables (shown in Figure 3). ~~EPIC observations, however, these variations occur smoothly.~~ With a relatively high-resolution simulated table, we can use a localized linear interpolation method to estimate the proper values. Multiple interpolations are needed for this method to decrease the number of LUT dimensions, which will cost more time than the analytic transfer inverse model method. The retrieval error of this method is determined by the resolution of the LUT, i.e., the higher the resolution, the higher retrieval accuracy. However, for multiple dimensional LUTs, the increase of resolution will increase the table size exponentially, which will increase computational cost substantially for the table building and inverse searching. Another possible method to increase the retrieval accuracy is using different interpolation methods. For example, if the value of LUT varies non-linearly with a variable, using high order interpolation method maybe better than using linear interpolation method (Dannenberg, 1998). ~~In physics, the retrieval accuracy is impacted by two main uncertainty sources: (1) the limited ability of EPIC in identifying cloud thermodynamic phase, which will affect the accuracy of cloud optical thickness retrieval, and 2) the uncertainty in estimating Cloud pressure.~~

2.2~~3~~.2 Method 2: Analytic transfer inverse model

For a long time, various efforts have been devoted to the study of radiative transfer in the atmosphere, including scattering, absorption, emission, and etc. (Chandrasekhar, 1960; Irvine 1964; Ivanov and Gutshabash 1974; van de Hulst, 1980, 2012; Ishimaru, 1999; Thomas and Stamnes, 2002; Davis and Marshak, 2002; Kokhanovsky et al., 2003; Marshak and Davis, 2005; Pandey et al., 2012; and etc.). In this study, we ~~are trying to~~ develop an analytic radiative transfer equation to analyze the radiative transfer at oxygen A and B bands. Through solving the analytic equation, we can retrieve the CTP information directly. The theory of CTP retrieval is similar for EPIC oxygen A-band and B-band observation. Here we use oxygen A-band as an example to study the radiative transfer model. For oxygen A-band, photon path length distribution is capable of describing vital information related to a variety of cloud and atmospheric characteristics.

$$I_\nu(\mu,\varphi;\mu_0,\varphi_0) = I_0(\mu,\varphi;\mu_0,\varphi_0)\int_0^\infty p(l,\mu,\varphi;\mu_0,\varphi_0)e^{-\kappa_\nu l}dl \qquad (1)$$

Where, $p(l)$ is photon path length distribution, κ_ν is the gaseous absorption coefficient at wave number ν, $\mu = cos(\theta), \mu_0 = cos(\theta_0)$, $(\theta,\varphi;\theta_0,\varphi_0)$ are zenith and azimuth angles for solar and sensor view respectively, I_0 and I_v are incident solar radiation and sensor measured solar radiation, respectively.

When clouds exist, the incident solar radiation is reflected to ~~outer space~~TOA in three primary ways. First, incident solar radiation is reflected by cloud top layer directly as a result of single scattering. Second, the incident solar radiation will penetrate into the cloud and be reflected back to TOA through cloud top via multiple scattering. Third, the incident solar radiation will pass through the cloud and arrive at the surface, after that it is reflected back into the cloud and finally scattered back to TOA through the cloud top. Due to the position of the EPIC instrument and the long distance between EPIC and Earth, we can consider that solar zenith angle and sensor view angle are nearly reverse. At oxygen A-band, the reflected solar radiation will be reduced due to oxygen absorption depending on photon path length distributions. Absorption is negligible in oxygen A-band's reference band. ~~For solar radiation at oxygen~~ Oxygen A-band and its reference band~~, they~~ are also attenuated by airmass and aerosol ~~that located above or below cloud~~ through Rayleigh scattering and aerosol extinction. In the standard atmospheric model, the optical depth of Rayleigh scattering (τ_{Ray}) at oxygen A-band (B-band) and its reference band is 0.026 (0.040) and 0.024 (0.042), respectively (Bodhaine et al., 1999). The absolute difference of Rayleigh scattering optical depth ($\Delta\tau_{Ray} = \tau_{Ray}^{In-band} - \tau_{Ray}^{Ref}$) between them is within 0.002. Compared to Rayleigh scattering, the difference of background aerosol optical depth ($\Delta\tau_{Aer}$) between ~~in-band~~absorbing and reference bands is smaller, within 0.0005. ~~However~~Therefore, the~~ir~~ attenuations from Rayleigh scattering and aerosol extinction at EPIC oxygen absorption and its reference band are close to each other. Thus, ~~we can~~when we use the ratio of EPIC measured reflectance at oxygen A-band and its reference band to derive the photon path length distribution and retrieve cloud information such as CTP, the impact of Rayleigh scattering and aerosol extinction can be simplified in the analytic transfer inverse model. ~~and then retrieve cloud information such as CTP.~~

To simplify the analytic transfer inverse model for EPIC observations, we made a series of assumptions, e.g., isotropic component, a plane-parallel homogenous cloud assumption with quasi-Lambertian reflecting surfaces~~, and etc~~. These assumptions have been widely used in radiative transfer calculation for cloud studies. In this model, μ and μ_0 are the same as in ~~Equation~~ Eq. (1), φ is the relative azimuth angle between ~~solar~~ Sun and satellite sensors; A_{surf} is the surface albedo; $\tau\cancel{t}_{O2}^{Top}$, $\tau\cancel{t}_{O2}^{Base}$, and $\cancel{t}\tau_{O2}^{Surface}$ are oxygen A-band absorption optical depth from TOA to cloud top layer, cloud bottom layer, and surface, respectively; $\Delta\tau\cancel{t}_{O2}^{Above-Cld}$, $\Delta\tau\cancel{t}_{O2}^{In-Cld}$ and $\Delta\tau\cancel{t}_{O2}^{Below-Cld}$ are layered oxygen A-band absorption optical depth above cloud, in cloud, and below-cloud, respectively; functions f mean their contribution to the ratio of measured reflectance at oxygen A-band (R_A) and refrence band (R_f). The detailed analysis of EPIC analytic transfer inverse model is shown as follows:

(1) **Above Cloud**: the reflected solar radiation is determined by the oxygen absorption optical depth above the cloud and air mass directly.

$$f\left(\Delta\tau\cancel{t}_{O2}^{Above-Cld}, \mu_0, \mu, \varphi\right) = f\left(\Delta\tau\cancel{t}_{O2}^{Above-Cld}\right) f\left(\mu_0, \mu, \varphi\right)$$

$$= a_0 \tau\cancel{t}_{O2}^{Top}\left(\frac{1}{\mu} + \frac{1}{\mu_0}\right) \quad (2)$$

Here, a_0 is a weight coefficient.

(2) **Within Cloud**: the reflected solar radiation is not only determined by oxygen absorption optical depth above cloud and in-cloud, but also by penetration related factors, e.g., ~~cloud optical depth~~COD. Due to photon penetration, oxygen parameter τt_{O2}^{Top} influences the enhanced path length absorption:

$$\Delta\tau t_{O2}^{In-Cld} = \tau t_{O2}^{Base} - \tau t_{O2}^{Top} \tag{3}$$

Equivalence theorem (Irvine, 1964; Ivanov and Gutshabash, 1974; van de Hulst 1980) is used to separate absorption from scattering:

$$\begin{aligned} f(\tau t_{O2}^{Top}, \Delta\tau t_{O2}^{In-Cld}, \mu_0, \mu, \varphi) &= f(\tau t_{O2}^{Top}, \Delta\tau t_{O2}^{In-Cloud}) f(\mu_0, \mu, \varphi) \\ &= f(\tau t_{O2}^{Top}) f_1(\mu_0, \mu, \varphi) + f(\Delta\tau t_{O2}^{In-Cloud}) f_2(\mu_0, \mu, \varphi) \end{aligned} \tag{4}$$

$f\left(\tau t_{O2}^{Top}\right)$ is determined by two absorption dependences: strong (~ $\sqrt{\tau t_{O2}^{Top}}$) and weak (~ τt_{O2}^{Top}).

$$f(\tau t_{O2}^{Top}) = a_1 \sqrt{\tau t_{O2}^{Top}} + b_1\left(\tau t_{O2}^{Top}\right) \tag{5}$$

Based on asymptotic approximation (*Kokhanovsky et al., 2003; Pandey et al., 2012*), the reflection of a cloud without considering below cloud interaction is given by ~~Equation~~ Eq. (6):

$$\begin{aligned} R(\tau t, \mu, \mu_0, T) &= R_0^{\infty}\left(\tau t, \mu, \mu_0\right) - TK(\mu)K(\mu_0) \\ &= R_0^{\infty}\left(\tau t, f_1(\mu, \mu_0)\right) - T f_2(\mu, \mu_0) \end{aligned} \tag{6}$$

Here, R_0^{∞} is the reflectance of a semi-infinite cloud, $K(\mu)$ is the escape function of μ, T is global transmittance of a cloud. T can be estimated by ~~Equation~~ Eq. (7), with the cloud optical thickness τ_{cld}, the asymmetry parameter , and a numerical constant α = 1.07 ~~a numerical constant~~.

$$T = \frac{1}{0.75\tau_{cld}(1-g)+\alpha} \tag{7}$$

f_1 and f_2 functions have a quadratic form as follows:

$$f_{i-1} = a_i T + b_i\left(\mu + \mu_0\right) + c_i T\left(\mu + \mu_0\right) + d_i \mu\mu_0, i = 2,3 \tag{8}$$

Combining Eq~~uation~~s. (4), (5) and (8), we can get the ~~equation~~ Eq. (9):

$$\begin{aligned} f\left(\tau t_{O2}^{Top}, \Delta t_{O2}^{Cld}, \mu_0, \mu, \varphi\right) = &\left(a_1 \sqrt{\tau t_{O2}^{Top}} + b_1\left(\tau t_{O2}^{Top}\right)\right)\left(a_2 T + b_2\left(\mu + \mu_0\right) + c_2 T\left(\mu + \mu_0\right) + d_2 \mu\mu_0\right) \\ &+ \Delta\tau t_{O2}^{In-Cloud}\left(a_3 T + b_3\left(\mu + \mu_0\right) + c_3 T\left(\mu + \mu_0\right) + d_3 \mu\mu_0\right) \end{aligned} \tag{9}$$

(3) **Below Cloud**: The equivalence theorem used for below cloud is similar to within cloud (Kokhanovsky et al., 2003; Pandey et al., 2012).

$$\begin{aligned} f\left(\Delta\tau t_{O2}^{Below-Cld}, \mu_0, \mu, \varphi\right) = &\; T\, \tau t_{O2}^{Surface} \frac{A_{Surf}}{1+(e_4 * T + f_4) * A_{Surf}} \\ &* \left(a_4 T + b_4\left(\mu + \mu_0\right) + c_4 T\left(\mu + \mu_0\right) + d_4 \mu\mu_0\right) \end{aligned} \tag{10}$$

Combining Eq~~uations~~s. (2), (9) and (10), we can get the total EPIC analytic transfer equation as follows

$$-log\left(\frac{R_A}{R_f}\right) = f\left(\Delta\tau_{O2}^{Above-Cld}, \mu_0, \mu, \varphi\right) + f\left(\tau_{O2}^{Top}, \Delta\tau_{O2}^{Cld}, \mu_0, \mu, \varphi\right) + f\left(\Delta\tau_{O2}^{Below-Cld}, \mu_0, \mu, \varphi\right) + \Delta\tau_{BG}\left(\frac{1}{\mu} + \frac{1}{\mu_0}\right) \quad (11)$$

In Eq~~uation~~. (11), $\Delta\tau_{BG}$ represents the sum of optical depth difference of background extinction (i.e., Rayleigh scattering $\Delta\tau_{Ray}$, aerosol extinction $\Delta\tau_{Aer}$, and O3 $\Delta\tau_{O3}$) between oxygen in-band and reference band, as shown in Eq~~uation~~. (12).

$$\Delta\tau_{BG} = \Delta\tau_{Ray} + \Delta\tau_{Aer} + \Delta\tau_{O3} \quad (12)$$

As stated in the previous subsection, in the standard atmospheric model with background aerosol loading, ($\Delta\tau_{Ray}, \Delta\tau_{Aer}, \Delta\tau_{O3}$) is approximately (0.002, 0.0005, -0.0005) and (-0.002, -0.0005, -0.002) respectively at oxygen A and B bands, thus $\Delta\tau_{BG}$ is approximately 0.002 and -0.0045 respectively at these two bands.

In this total analytic equation, there are ~~16~~ 17 coefficients ($a_0, a_1, b_1, a_2, \ldots d_4, e_4, f_4$), which can be calculated through nonlinear regression algorithm according to a series of simulated values for different atmospheric conditions. Based on ~~Equation~~ Eq. (11), we can finally obtain a quadratic equation, $\boldsymbol{A}\sqrt{\tau_{O2}^{Top}}^{\boldsymbol{2}} + \boldsymbol{B}\sqrt{\tau_{O2}^{Top}} + \boldsymbol{C} = \boldsymbol{0}$, where the parameters A, B and C ~~(not shown here)~~ can be derived from ~~Equation~~ Eq. (11) directly, as shown in Eq~~uation~~. (13).

$$A = a_0\left(\frac{1}{\mu} + \frac{1}{\mu_0}\right) + b_1\left(a_2 T + b_2(\mu + \mu_0) + c_2 T(\mu + \mu_0) + d_2\mu\mu_0\right) \quad (13.1)$$

$$B = a_1\left(a_2 T + b_2(\mu + \mu_0) + c_2 T(\mu + \mu_0) + d_2\mu\mu_0\right) \quad (13.2)$$

$$C = -log\left(\frac{R_A}{R_f}\right) - \Delta\tau_{BG}\left(\frac{1}{\mu} + \frac{1}{\mu_0}\right) - \Delta\tau_{O2}^{In-Cloud}\left(a_3 T + b_3(\mu + \mu_0) + c_3 T(\mu + \mu_0) + d_3\mu\mu_0\right) - T\,\tau_{O2}^{Surface}\frac{A_{Surf}}{1 + (e_4 * T + f_4) * A_{Surf}}\left(a_4 T + b_4(\mu + \mu_0) + c_4 T(\mu + \mu_0) + d_4\mu\mu_0\right) \quad (13.3)$$

When these parameters (i.e., A, B and C) are obtained from EPIC observation data and other data source, we can easily solve the quadratic equation to retrieve cloud top O2 absorption depth, and then CTP.

2.3 Detailed retrieval algorithm

As previously stated, in method 2, the analytic EPIC equation (i.e., ~~Equation~~ Eq. (11)) is key for the CTP retrieval. To derive the coefficients of ~~Equation~~ Eq. (11), a series of model simulations for various atmospheric conditions are needed. Thus, developing a radiative transfer model to simulate the EPIC measurements at A- and B-bands and their reference bands is the first thing we need to complete.

~~4~~2.3.1 Oxygen A- and B-band absorption coefficients calculation

To simulate the EPIC measurements, one of the most important steps is calculating oxygen absorption coefficients at oxygen A-band and B-band. In this step, the ~~latest~~ HITRAN

2016 database ~~(*Gordon et al., 2017*)~~ is used to provide the absorption parameters, and the LBLRTM package ~~(*Clough et al., 2005*)~~ is used to calculate oxygen absorption coefficients layer by layer. In our algorithm, the whole Earth atmosphere is divided by 63 layers.

Since oxygen absorption coefficients are pressure (or pressure-squared) and temperature dependent, and the line shapes (k_i) of oxygen A- and B-bands are well fitted as Lorentzian in the lower atmosphere, the relationship can be written as follows:

$$k_i = \frac{S_i}{\pi}\frac{\alpha_i}{(v-v_i)^2+\alpha_i^2} \qquad (~~12~~14)$$

$$\alpha_i = \alpha_i^0 \frac{P}{P_0}\left(\frac{T_0}{T}\right)^{\frac{1}{2}},\ S_i = S(T_0)\frac{T_0}{T}\exp\left[1.439E\left(\frac{1}{T_0}-\frac{1}{T}\right)\right] \qquad (~~13~~15)$$

Where S_i is the line intensity, v_i and α_i are the line center wave number and half width, respectively; P_0 and T_0 are standard atmospheric pressure and temperature, respectively.

~~An unfortunate result of this is that cloud levels at a given pressure-weighted oxygen absorption depth~~In the simulation of EPIC measurements, the atmospheric layer at a given layer-average pressure can have drastically different temperature ~~heights~~ depending on the atmospheric profile in use. ~~We have used~~To ensure the accuracy of simulation, we need to use the LBLRTM package to calculate oxygen absorption coefficients~~parameters~~ for each pressure/temperature profile, ~~;~~ which is a time-consuming process. Our goal has been to find a simple and fast method to calculate oxygen absorption coefficients~~conversion function from pressure to altitude~~ for different atmospheric profiles. Based on the study of Chou and Kouvaris (1986), Min et al. (2014) proposed a fast method to calculate oxygen absorption optical depth for any given atmosphere by ~~Using~~ using a polynomial fitting function, as shown in Eq~~uation~~. 16. ~~, fitting coefficients can be determined for oxygen absorption and applied to any given atmosphere (Min et al., 2014; Chou and Kouvaris, 1986).~~

$$\ln(A_{vLM}) = [a_0(v,P) + a_1(v,P)\times(T_{LM}-T_{mL}) + a_2(v,P)\times(T_{LM}-T_{mL})^2]\times\rho_{O_2} \qquad (~~14~~16)$$

Where A_{vLM} is optical depths for layer L, spectral point v, and atmosphere model M; ρ_{O_2} is molecular column density ($\frac{molecules}{cm^2}\times 10^{-23}$); T_{LM} is the average temperature for layer L for a given atmosphere; and T_{mL} is average temperature over all six typical geographic-seasonal model atmospheres (M1 to M6, i.e., tropical model, mid-latitude summer model, mid-latitude winter model, subarctic summer model, subarctic winter model, and the U.S. Standard (1976) model) for layer L. To derive the coefficients a_0, a_1, and a_2, we first~~ly~~ calculated oxygen optical depth coefficients for all typical atmospheres (M1 to M6) by using LBLRTM package, and then selected three of them (e.g., M1, M5, and M6) to calculate the polynomial fitting coefficients. This method has been successfully used by Min et al. (2014) to simulate the high resolution oxygen A-band measurements.

~~4~~2.3.2 Fast radiative transfer model for simulating high-resolution oxygen A- and B-bands

At oxygen A and B absorption bands, there are lots of absorption lines, therefore w~~W~~e cannot simply calculate narrowband mean optical depth and then calculate the radiation for various atmospheric conditions when simulating EPIC narrowband measurements. The correct way is described as follows: firstly, simulate the solar radiation spectrum $S(k(\lambda))$ under specific atmospheric conditions, then integrate the spectrum with EPIC narrowband filter $R(k(\lambda))$ to obtain simulated narrowband measurements (Equation Eq. 15(17)).

$$R(\lambda) = \int S(k(\lambda))R(k(\lambda))d\lambda \neq R(\overline{k(\lambda)}) \qquad (1517)$$

With the high spectrum resolution oxygen absorption coefficient data, we can simulate the high resolution upward diffuse oxygen A-band or B-band spectrum through DISORT code (Stamnes et al., 1988) for any given atmospheric condition, which has various surface albedo, SZA, cloud optical depthCOD, cloud top heightCTH (pressureCTP), and cloud geometric (pressure) thickness. However, due to the high spectrum resolution, it is very time-consuming when performing line by line (LBL) calculations. Thus, developing a fast radiative transfer model for simulating high resolution oxygen A-band and B-band spectrum is necessary.

In this project, the double-*k* approach is used to develop a fast radiative transfer model for oxygen A-band and B-band respectively. [Min and Harrison 2004; Duan et al, 2005] proposed a fast radiative transfer model. In their approach, the radiation from absorption and scattering processes of cloud and aerosol are split into the single- and multiple-scattering components: The single scattering component is computed line-by-line (LBL), while multiple scattering (second order and higher) radiance is approximated.

$$\begin{aligned} I &= I^{ss}(\lambda) + I^{ms}(\lambda) \\ &\approx I^{ss}[Z^h(p,tT),P^h,\lambda] + I^{ms}[Z^h(p,tT),P^h,\lambda] \\ &\approx I^{ss}[Z^h(p,tT),P^h,\lambda] + I^{ms}[Z^l(p,tT),P^l,\lambda] \\ &\approx I^{ss}[Z^h(p,tT),P^h,\lambda] + I^{ms}\{F[Z^l(p,tT),P^l,k(\lambda_i)]\} \end{aligned} \qquad (1618)$$

Equation Eq. 16 (18) is from Equation Eq. (1) in Duan et al. (2005): *ss* and *ms* mean single and multiple scattering, respectively. Z is the optical properties of the atmosphere as a function of pressure *p* and temperature *Tt*, with P being the phase function of that layer. *Hh* and *l* represent higher and lower number of layers and streams, respectively. F is the transform function between wave number space and k space, defined from a finite set of $k(\lambda_i)$.

The application of Double-*k* approach in oxygen A-band has been presented in detail in Duan et al. 2005. Here we take oxygen B-band as an example. The detailed fast radiative transfer model for simulating high-resolution oxygen B-band is as follows: The first order scattering radiance is calculated accurately by using a higher number of layers and streams for all required wavenumber grid points. The multiple-scattering component is extrapolated and/or interpolated from a finite set of calculations in the space of two integrated gaseous absorption optical depths to the wavenumber grids: a double-*k* approach. The double-*k* approach substantially reduces the error due to the uncorrelated nature of overlapping absorption lines. More importantly, these finite multiple-scattering radiances at specific *k* values are computed with a reduced number of layers and/or streams in the forward radiative transfer model. To simulate an oxygen B-band spectrum with high accuracy, 33 *k* values and 99 calculations of radiative transfer are chosen in our program. This results in around a hundred-fold time reduction with respect to the standard forward radiative transfer calculation.

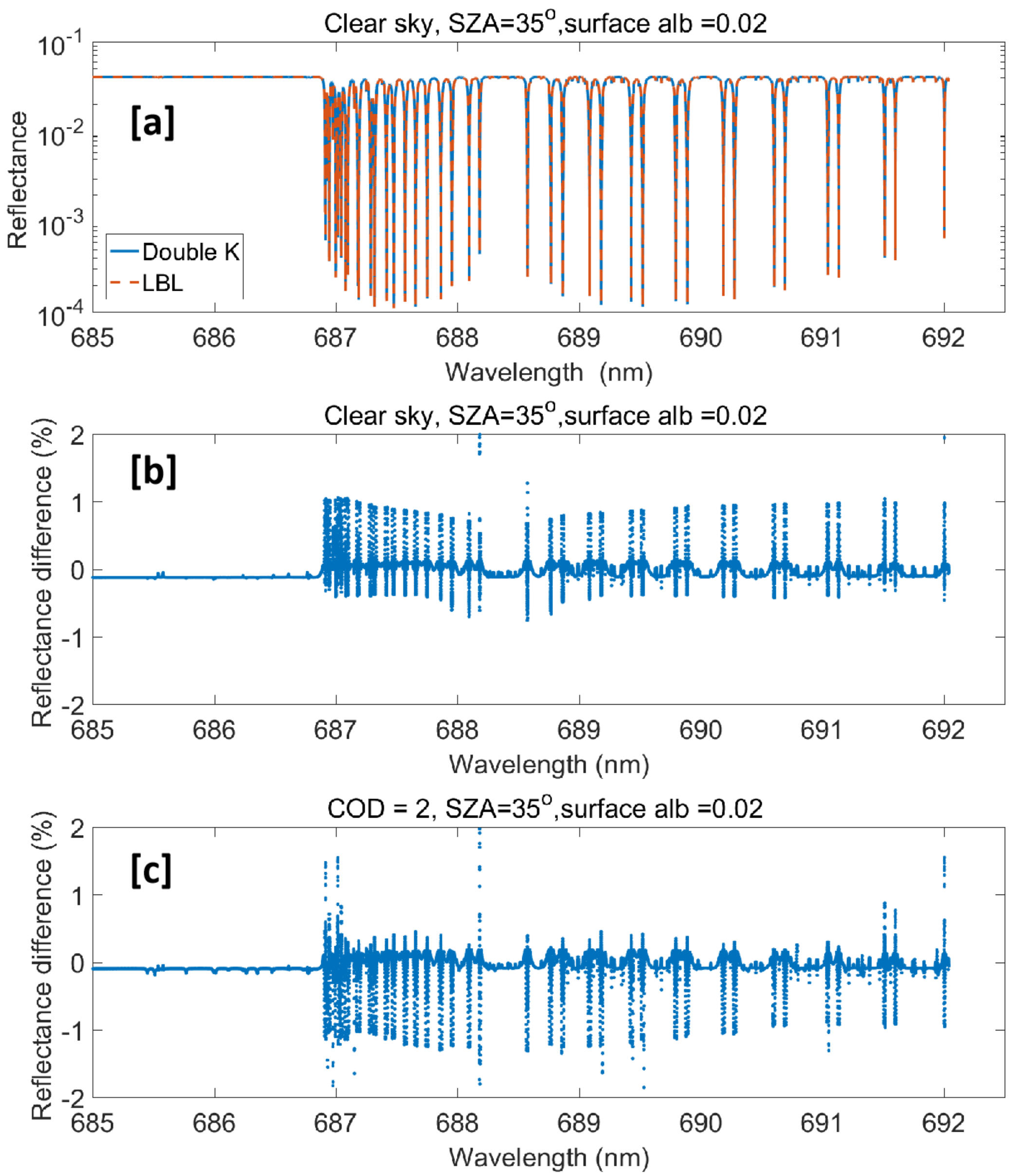


Figure 2. [a] High resolution reflectance at EPIC O2 B-Band simulated by fast radiative model (double-k) and benchmark (LBL); Difference between simulated reflectance by double-k and LBL for a clear sky case [b] and a ~~cirrus~~ thin liquid water cloud case with COD=2 [c]. Here SZA and view angle =35°, surface albedo = 0.02, aerosol optical depth = 0.08, and reflectance difference (%) = 100*((double-k) – LBL)/LBL.

As shown in Figure 2, under clear sky and thin liquid water cloud situations, the simulated high resolution upward diffuse oxygen B-band spectra from LBL calculation and double-k approach are compared. The spectrum difference between LBL calculation and double-k approach is very small ~~and hard to tell directly~~ (Figure 2a). Under both situations, most of the relative difference between these two methods are under 0.5%. The obvious relative difference (>1%) occurs only in the wavelength range with high absorption optical depth, which has little contribution to the integrated solar radiation. Therefore, for the simulated narrowband measurements at EPIC oxygen B-band, the relative difference between LBL and double-k approach is much smaller than that of the high resolution spectrum, which is less than 0.1% for ~~both~~ clear day. Compared to clear sky situation, the relative difference for ~~and~~ cloud situations can be bigger. As ~~(~~shown in Table 1, the relative difference is -0.06% and -0.32% for typical high level optical thin cloud and low-level thick cloud situations, respectively~~)~~. ~~For optically thick cloud situations, the accuracy of the double-k approach is similar to that of thin cloud situations.~~The comparison of simulated narrowband measurement at EPIC oxygen A-band channel (764 nm) is also shown in Table 1, the relative differences between LBL and double-k approach are -0.06%, 0.21% and 0.23% for clear day, high level thin cloud and low level thick cloud cases, respectively. In general, the accuracy of double-k approach for both oxygen A and B absorption bands is high.

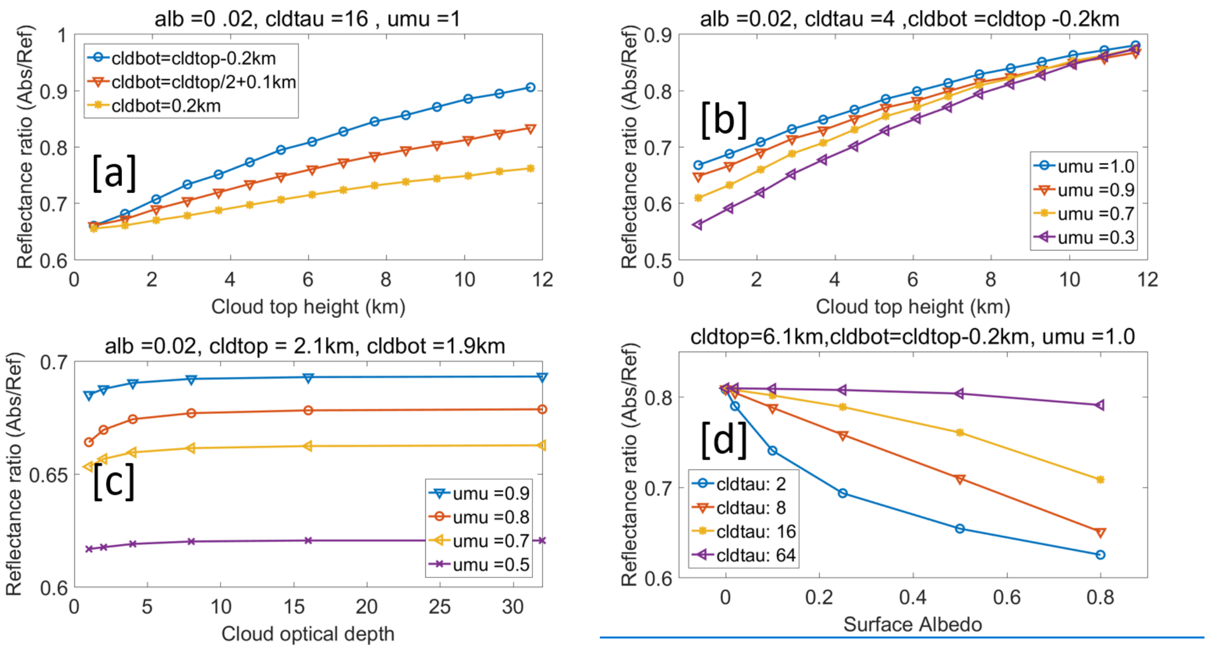
Table 1. Comparison of simulated narrowband measurement at EPIC A- and B-Band channels

~~Case~~	~~Line by line~~	~~Double-k~~	~~Difference~~
~~Clear day~~	~~0.026963~~	~~0.026985~~	~~+0.08%~~
~~Thin Cloud~~	~~0.084046~~	~~0.084033~~	~~-0.02%~~

Case (SZA=35, surface albedo =0.02)		Line by Line	Double k	Relative Difference
Clear Day	688 nm	0.026963	0.026985	+0.08%
	764 nm	0.013979	0.013970	-0.06%
Thin cloud (COD=2, 8.3-8.5 km, liquid)	688 nm	0.098444	0.098131	-0.32%
	764 nm	0.071359	0.071507	+0.21%
Thick cloud (COD=16, 1.5-2.9 km, liquid)	688 nm	0.396354	0.396117	-0.06%
	764 nm	0.233937	0.234485	+0.23%

~~4~~2.3.3 Simulation of oxygen A- and B-bands for different atmospheric conditions

Using the EPIC measurement simulation package, we made a series of simulations with different settings for surface albedo, solar zenith angle, ~~cloud optical depth~~COD, CTH~~cloud top height~~ (~~pressure~~CTP), and cloud geometric (pressure) thickness (or cloud bottom height). The results of these simulations consist of a data table, which can be used not only to calculate the coefficients for the analytic equation, but also to study the ~~sensibility~~ sensitivity of every ~~variant~~variable.



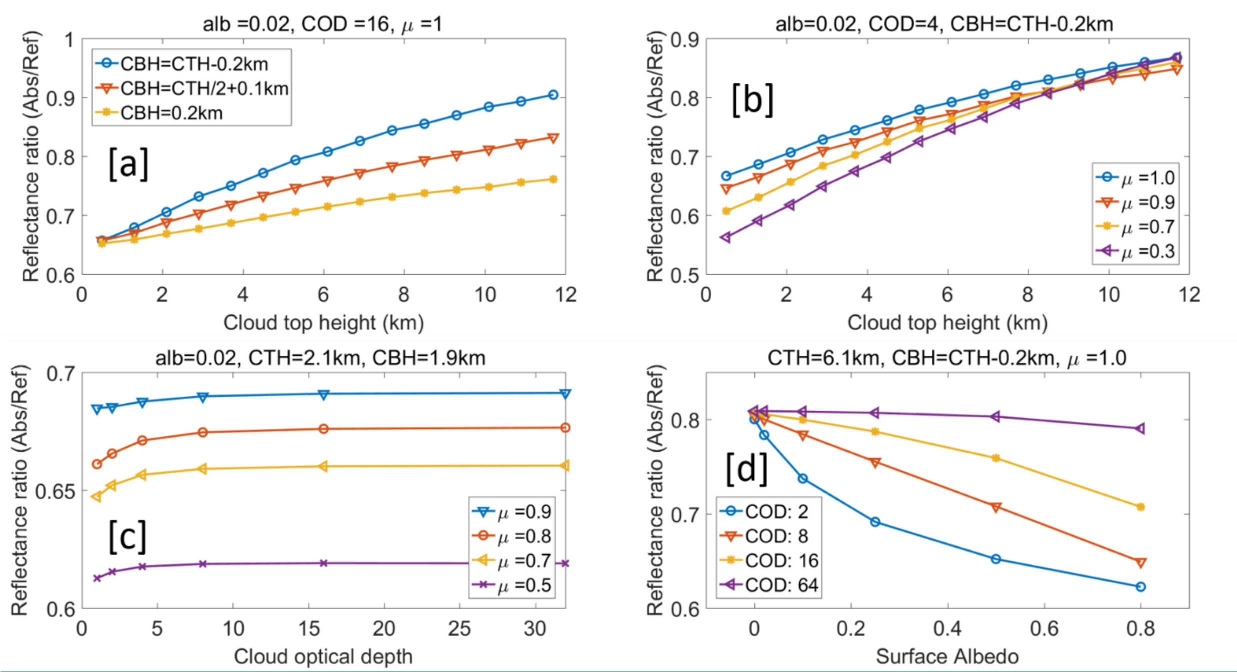


Figure 3. Ratio of simulated reflectance measurements for EPIC B-band to B-band reference with different surface albedo (alb), ~~cloud optical depth~~COD, μ (cosine of solar zenith angle), cloud top height (CTH) and cloud bottom height (CBH).

According to the previous theory study, the ratio of reflectance radiance (i.e., absorption to the reference) at TOA is determined by the photon path length distribution at oxygen A/B bands: the larger the mean photon path length, the stronger the absorption, and the smaller the reflectance ratio. To make the figures easy to view and understand, we use cloud top and bottom geometric height to represent CTP~~cloud top pressure~~ and thickness information in Figure 3. As shown in Figure 3a, the ratio of upward diffuse radiance at oxygen B-band and its reference band is sensitive to the cloud top height (pressure). The higher the ~~cloud top height~~CTH, the larger the ratio. At the same time, this ratio is affected by the cloud bottom height (or cloud geometric thickness) when the other cloud parameters are fixed, the lower the cloud bottom (or the larger the cloud geometric thickness), the smaller the ratio. It is consistent with the theory analysis: (1) the higher the ~~cloud top height~~CTH, the shorter the mean photon path length, and the weaker the absorption; (2) when the ~~cloud optical depth~~COD is given, larger cloud geometric thickness means smaller cloud density, then the sunlight can penetrate deeper into the cloud, which results in a longer mean photon path length. In Figure 3b, for clouds with given ~~cloud top height~~CTH, ~~cloud optical depth~~COD and geometric thickness, the ratio decreases with the solar and view angles. This ~~is easy to understand~~can be understood as: the larger the solar and view angles, the longer the mean photon pathlength, and the stronger the absorption. In Figure 3c, for clouds with given ~~cloud top height~~CTH and geometric thickness, when the ~~cloud optical depth~~COD is small (e.g., COD <5), the reflectance ratio increases with ~~cloud optical depth~~COD. However, when ~~cloud optical depth~~COD is larger than 16, the effect of ~~cloud optical depth~~COD is small. This is because the larger the ~~cloud optical depth~~COD, the shallower the sunlight penetration, and the shorter the mean photon pathlength. In Figure 3d, for clouds with given ~~cloud optical depth~~COD, CTP, and geometric thickness, the ratio decreases with surface albedo. The smaller the ~~cloud optical depth~~COD, the stronger the impact of the surface albedo. This is because the ~~heavy~~ thick cloud prevents the incident sunlight from passing through it to reach the surface, and also prevents the reflected light from going back to the TOA.

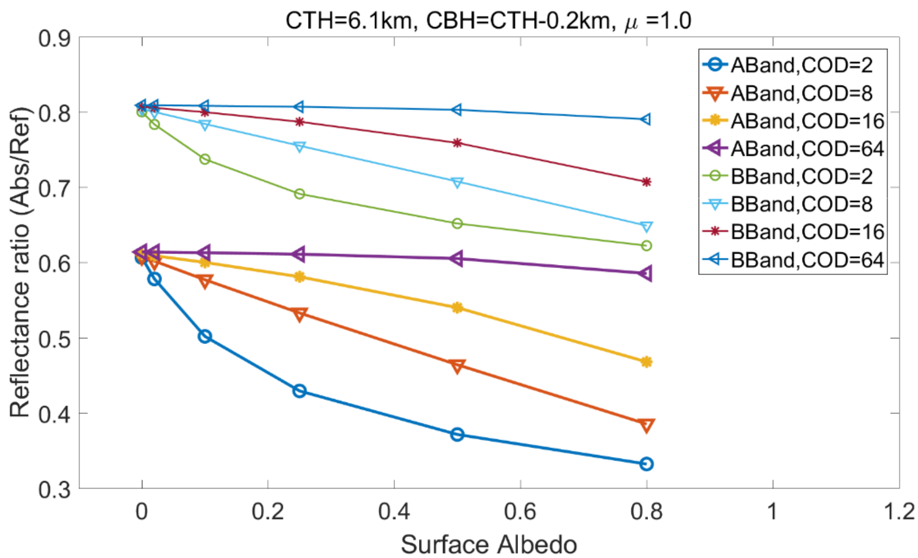


Figure 4. Ratio of simulated reflectance measurements for EPIC A and B absorption band to reference band with different surface albedo.

For oxygen A-band, the ratio of upward diffuse at absorption and reference bands shows similar characteristics as for oxygen B-band. Compared to oxygen B-band, under the same atmospheric conditions, the oxygen absorption at A-band is stronger, and the ratio of A-band to its reference band has smaller values (shown in Figure 4). As stated previously, for land area that covered with plants, the surface albedo may change substantially from oxygen B-band to A-band due to the presence of the red edge. Therefore, accurate spectral data of surface albedo for CTP retrieval is vitally important, especially for optically thin clouds.

3. Application and validation of the CTP retrieval method

3.1 Case studies of ~~cloud top pressure~~CTP retrieval

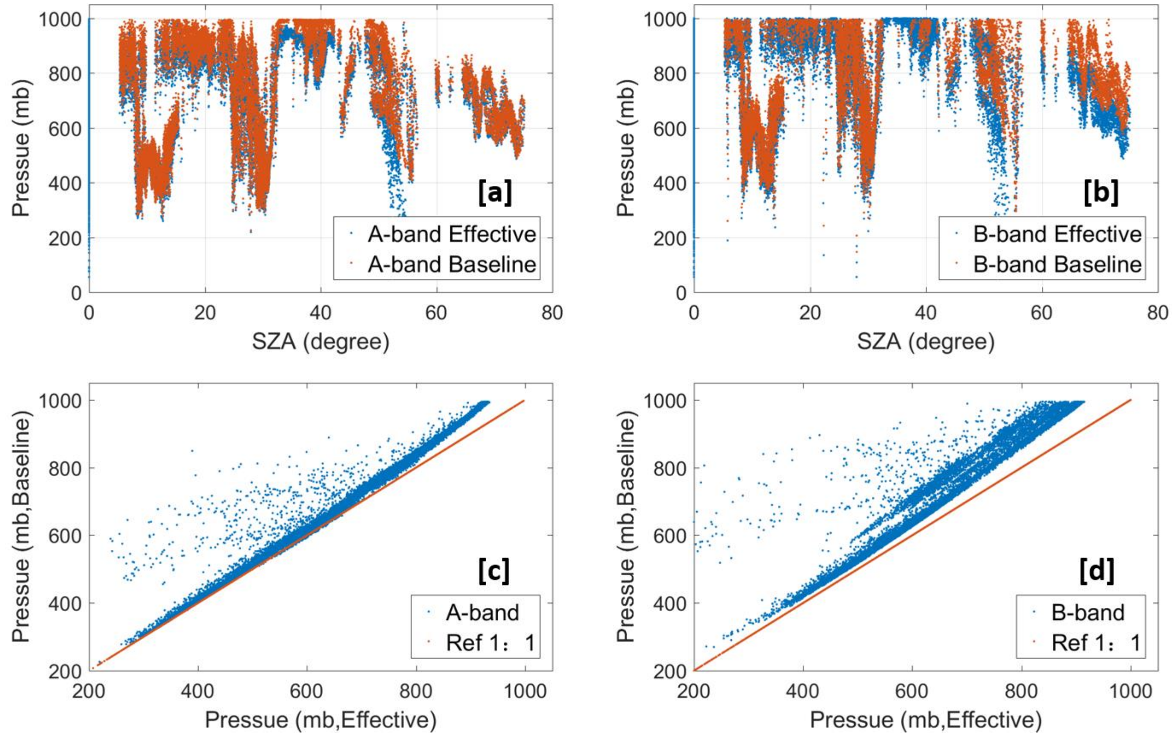
The dataset of DSCOVR EPIC measurements at GMT 00:17:51 on July 25, 2016 is used for the case studies. The reflectance at oxygen A and B bands with related solar zenith and viewing angles are obtained from the EPIC level 1B data; COD information (retrieved from other EPIC channels) is obtained from EPIC level 2 data. The surface albedo data is obtained from Global Ozone Monitoring Experiment 2 (GOME-2) Surface Lambertian-equivalent reflectivity (LER) data. The detailed information of dataset is shown in the acknowledgements and dataset. To reduce the impact of the Earth surface, we selected the region located in spatial range of (S75° to N85°, W177° to W175°) for case studies, which is mainly covered by ocean. To constrain the influence of surface albedo and broken clouds, only pixels with total cloud cover~~ing~~ (i.e., EPIC Cloud mask = 4), surface albedo less than 0.05, and liquid assumed COD larger than 3 are considered. In the selected region, around 10000 pixels are finally chosen for case studies.

In our retrieval algorithm, we have two kinds of retrieval results: baseline CTP and retrieved CTP. The baseline CTP is used as a reference for the retrieved CTP. It is similar to the effective CTP in Yang et al., (~~2013~~2019), which does not consider cloud penetration. The retrieved CTP is calculated by the analytic equation, which considers the in-cloud and below-cloud interaction.

During the baseline CTP calculation, the impact of penetration in-cloud is ~~ignorable~~ignored, and the incident light that reached cloud top is assumed reflected back directly. As shown in ~~Equation~~ Eq. ~~15~~(19), the baseline absorption optical depth τ_{base} is derived from the ratio of upward diffuse at absorption bands and their reference bands directly. According to the model calculated oxygen A and B bands absorption optical depth profile at the specific solar zenith angle, the baseline CTP can be derived directly.

$$\tau_{base} = \log\left(-\frac{R_{abs}}{R_{ref}}\right) / \left(\frac{1}{\cos(\theta_{sza})} + \frac{1}{\cos(\theta_{view})}\right) \qquad (~~15~~19)$$

As shown in Figure ~~4~~5, the baseline CTP value at A-band is slightly higher than the effective CTP from NASA ASDC L2 data. But the baseline CTP value at B-band is substantially higher than the effective CTP from NASA ASDC L2 data. For both A-band and B-band, the difference between baseline CTP and effective CTP increases with the CTP. For low-level clouds, the mean differences of them are up to 60 mb and 100 mb at A-band and B-band, respectively. The difference may be mainly from the calculation of oxygen A and B bands absorption coefficients or the absorption optical depth profile.


[a]
A-band Effective
A-band Baseline
Pressue (mb)
SZA (degree)
[b]
B-band Effective
B-band Baseline
[c]
A-band
Ref 1：1
Pressue (mb,Baseline)
Pressue (mb,Effective)
[d]
B-band
Ref 1：1

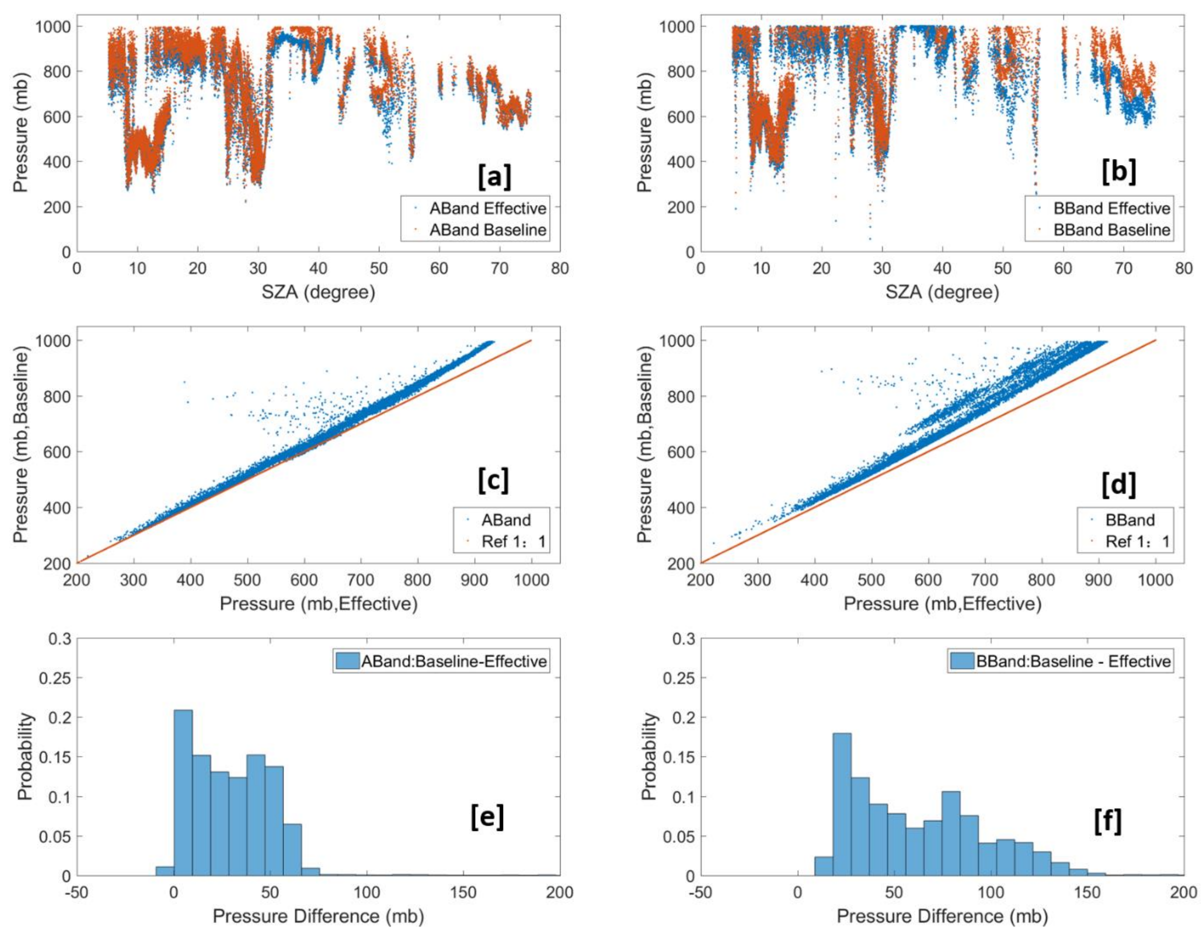
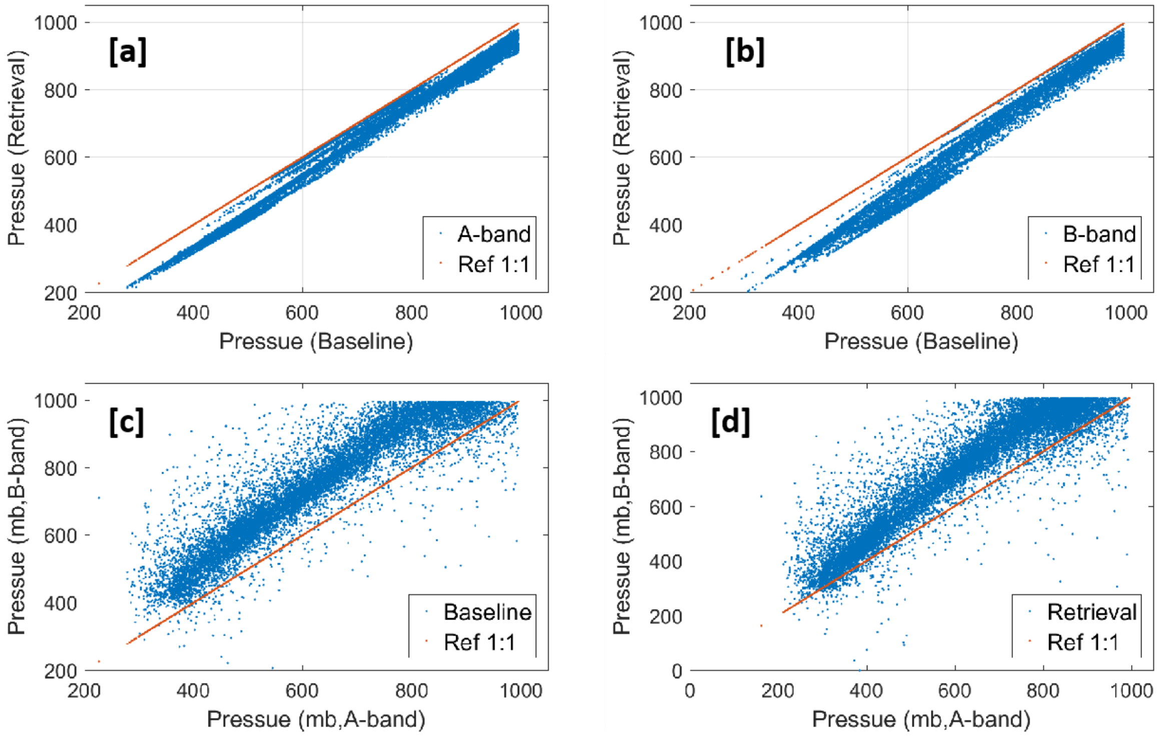

[a]
ABand Effective
ABand Baseline
Pressure (mb)
SZA (degree)
[b]
BBand Effective
BBand Baseline
[c]
ABand
Ref 1：1
Pressure (mb,Baseline)
Pressure (mb,Effective)
[d]
BBand
Ref 1：1
ABand:Baseline-Effective
Probability
Pressure Difference (mb)
[e]
BBand:Baseline - Effective
[f]

Figure ~~4~~5. The comparison of effective CTP (reference from NASA ASDC data) and baseline values from our retrieval algorithm for EPIC A and B bands.

Based on the simulated reflectance ratio under different atmospheric conditions, we can calculate the coefficients for the analytic radiative transfer equations by using a nonlinear fitting algorithm. The coefficients for different SZA's are calculated individually to reduce the fitting error. Based on the calculated coefficients, we can retrieve the CTP with DISCOVR EPIC observation data at oxygen A and B bands.

During the CTP retrieval, with the exception of the previously mentioned analytic equation coefficients, we can get the surface albedo data from GOME, obtain reflectance data, solar zenith and view angles, ~~cloud optical depth~~COD, etc. from the NASA ASDC data file. Another very important step in the retrieval processing is the acquisition of cloud pressure thickness data, which has a substantial impact on the retrieval results. We currently use a statistical approach (i.e., cloud pressure thickness (mb) = 2.5* ~~cloud optical depth~~COD +~~26~~23) to estimate the cloud pressure thickness based on ~~cloud optical depth~~COD. As shown in Figure ~~5a~~ 6a-6d~~and 5b~~, the retrieved CTP when considering cloud penetration is smaller than baseline CTP. For this case, the mean difference between baseline CTP and retrieved CTP for oxygen A-band and B-bands are around 57 mb and 85 mb, respectively, which is consistent with theoretical expectations. For clouds with a given CTP, the mean photon path length will increase substantially when considering cloud penetration~~ and interaction~~. A decrease in retrieved CTP will result in order to match the measurement ratio of absorption to reference. Compared to the O2 A-band, both baseline CTP and retrieved CTP for the O2 B-band are larger (Figure ~~5c~~ 6e-6h~~and 5d~~). This is because the absorption of solar radiation in the O2 B-band is weaker than that of the O2 A-band, and the incident light at oxygen B-band can penetrate deeper into the cloud, allowing more light to pass through. The difference in retrieved CTP between B band and A band (approx. ~~101~~ 93 mb with standard deviation of 83 mb) is generally reduced in comparison to baseline B band and A band (approx. ~~129~~ 114 mb with standard deviation of 73 mb). This indicates, as expected, more photon penetration correction for B-band than A-band.


[a]
Pressue (Retrieval)
Pressue (Baseline)
A-band
Ref 1:1
[b]
Pressue (Retrieval)
Pressue (Baseline)
B-band
Ref 1:1
[c]
Pressue (mb,B-band)
Pressue (mb,A-band)
Baseline
Ref 1:1
[d]
Pressue (mb,B-band)
Pressue (mb,A-band)
Retrieval
Ref 1:1

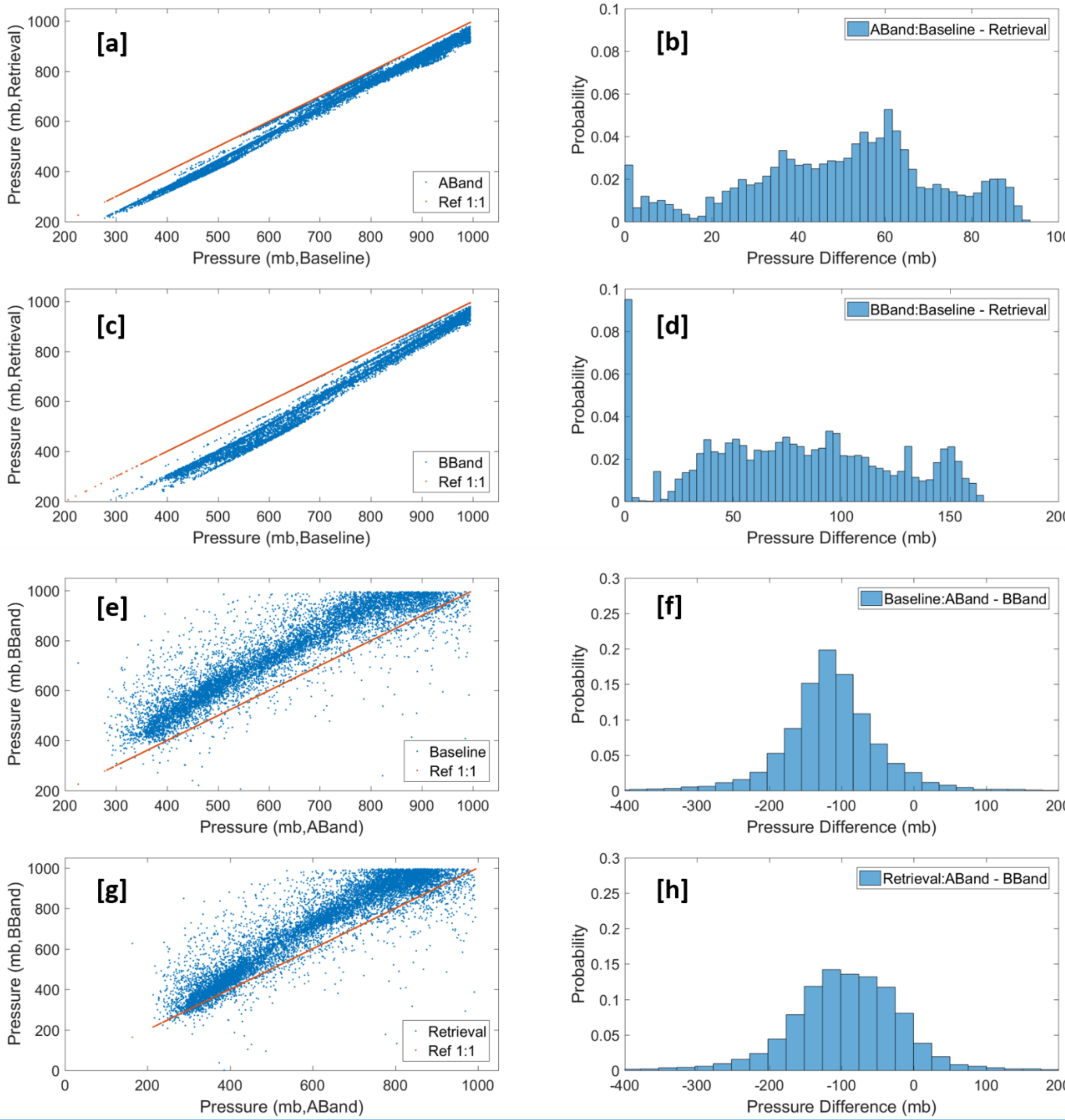


Figure ~~5~~6. (~~a and b~~a-d) The comparison of retrieved CTP and baseline values for EPIC A and B bands; (~~c and d~~e-f) the comparison of retrieved CTP and baseline values between EPIC A- and B- bands.

We also used the LUT based method to do the retrieval for the same observation data, because both methods share the same EPIC simulation package and the same simulated data table, the results of which are similar.

3.2 Validation of the retrieval method

To validate the analytic transfer inverse model method for CTP retrieval, we used another independent measurement of CTP, i.e., cloud layer top pressure from Cloud-Aerosol Lidar and

Infrared Pathfinder Satellite Observations (CALIPSO, Vaughan et al., 2014) as a reference. For the previously stated case, i.e., DSCOVR EPIC measurements at GMT 00:17:51 on July 25, 2016, we used the cloud layer data from CALIPSO IIR Version 4.2 Level 2 product with 5 km resolution at GMT 00:01:47 on July 25, 2016 as its reference to do validation. To constrain the error from spatial differences between different satellite measurements, we only chose the pixels of EPIC and CALIPSO measurements with a spatial distance of within 0.1º (degree of latitude or longitude) to make comparisons. For the EPIC measurements, the same as previously stated, only pixels with total cloud cover (i.e., EPIC Cloud mask = 4), surface albedo less than 0.05, and liquid assumed COD larger than 3 are considered. As shown in Figure 7a, there are a series of pixels (around 400 cases) from EPIC and CALISPO measurements can be used for the validation analysis. For the convenience of reading, we perform the analyses by using the case number as x axis. Figure 7b shows the comparisons of cloud layer top pressure from CALIPSO and different CTPs (i.e., effective CTP, baseline CTP, and retrieved CTP) from EPIC measurements. Figure 7c shows the cloud layer number measured by CALIPSO. According to Figures 7b and 7c, we can get some results: under single layer cloud situations, the CTPs derived from EPIC measurements are close to the CTP from CALISPO; under multi-layer cloud situations, the CTP derived from EPIC measurements are larger than the CTP from CALISPO. Figure 7d shows the expanded view of the Figure 7b for some cases under single layer cloud situations. For these single layer cloud cases (with case number 46 ~ 156), the mean values of CTP of CALIPSO, EPIC effective, EPIC baseline and EPIC retrieval are 846, 834, 866 and 850 mb, respectively. Compared to the CTP from CALIPSO measurements , the EPIC effective and baseline CTPs are 12 mb smaller or 20 mb larger, respectively; the EPIC retrieval with consideration of photon penetration is only 4 mb larger. This shows that our method for the CTP retrieval is valid and accurate under single layer cloud situations with COD > 3 and low surface albedo. Under multi-level cloud situations, the high-level clouds are often thin clouds, which can be detected by CALIPSO but hard to derive by our retrieval method. It is because the EPIC retrieved CTP mainly shows the pressure of cloud layer that reflects the major part of incident sun light.

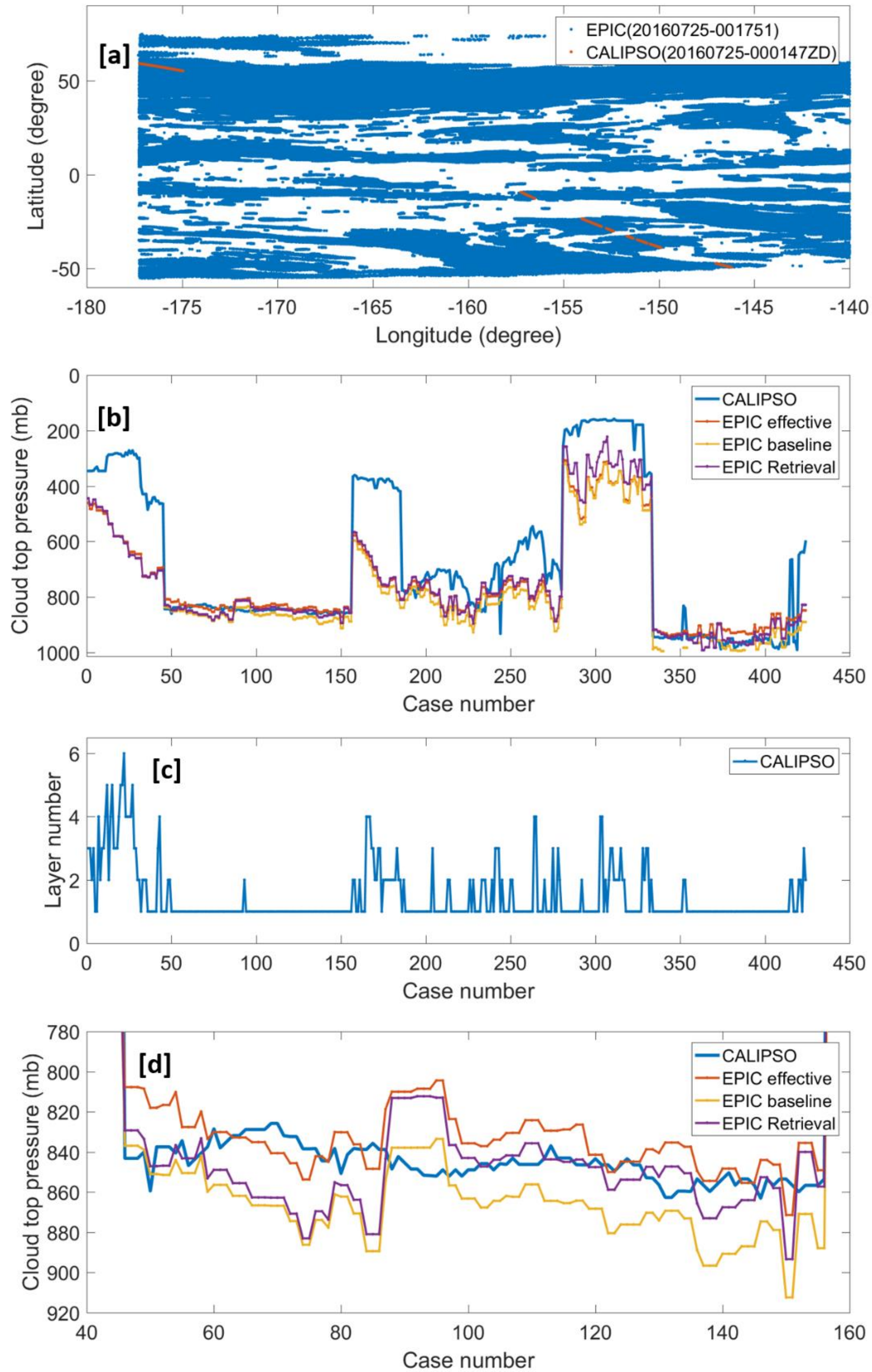
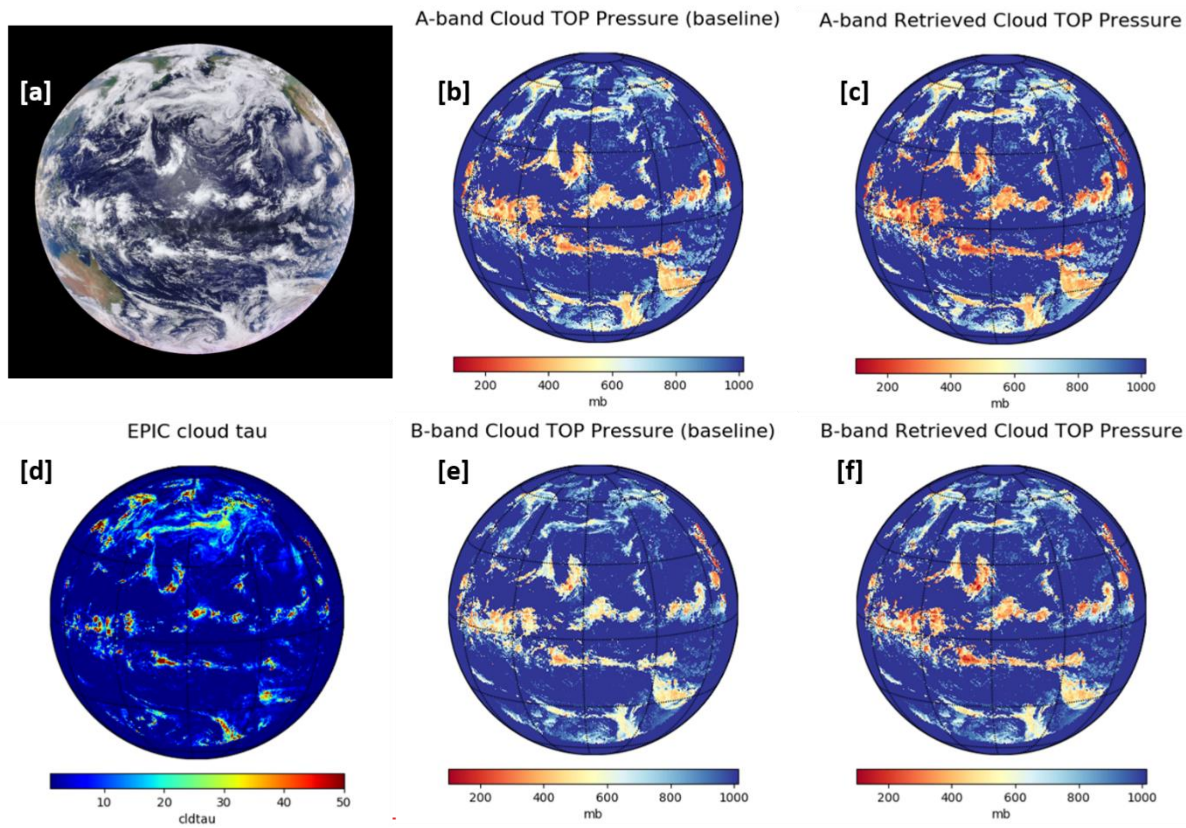


Figure 7. (a) The geolocation match of EPIC measurement at GMT 00:17:51 and CALISPO measurement at GMT 00:01:47 on July 25, 2016; (b) the comparisons of cloud layer top pressure from CALIPSO measurements and the CTPs derived from EPIC measurements; (c) the cloud layer number from CALIPSO measurements; and (d) the expanded view of (b) for some cases under single layer cloud situations.

3.3 Retrieval of global observation

We applied our retrieval algorithm on the global DISCOVR EPIC measurement data at oxygen A and B bands. During the retrieval, only pixels with total cloud cover~~ing~~ (i.e., cloud mask index of 4), surface albedo < 0.25, and ~~cloud optical depth~~COD >= 3 are considered. To make the pictures easy to visualize and analyze~~,~~ ~~we set~~ all invalid values are plot as white (or blank) pixels~~to 1013; same as the background sea level pressure~~.

Figure ~~6a~~ 8a shows the synthesized RGB picture of EPIC measurements at GMT time 00:17:51 on July 25, 2016. At this point in time the sun light covers most of the Pacific Ocean. In this figure, the white pixels represent cloud cover. Figure ~~6d~~ 8b shows the global ~~cloud optical depth~~COD (NASA ASDC L2 data), in which the white areas and colorful areas indicate the clear sky areas and cloudy areas, respectively. On the whole, the ~~highlights~~ cloudy areas are consistent with the RGB image. The highlight (red) areas indicate that the cloud systems there contain optically heavy clouds. Figure 8c shows the A-band effective CTP (NASA ASDC L2 data), where the white areas indicate clear sky or no valid values, warm (brown) and cold (blue) color areas indicate high-level and low-level clouds, respectively. According to the A-band effective CTP, the high-level clouds are dominant in the equatorial area, and the low-level clouds play a major role in the cloud systems in the Northern Pacific area. Figure ~~6b~~ 8d and ~~6c~~ 8e show the baseline and retrieved CTP at A-band, respectively, which ~~also highlights~~ cloudy areas ~~(white to brown)~~ are consistent with ~~the RGB image~~the A-band effective CTP image on the whole. Due to the filtering setting in the CTP retrieval algorithm, there are more white pixels (invalid values) in these two figures. The difference of A-band retrieved CTP and A-band effective CTP is shown in Figure 8d. The A-band retrieved CTP is overall smaller than A-band effective CTP, which difference is within 100 mb. The highlighted (brown or red) areas are located in the high level clouds areas or large COD areas. This indicates that the complexity of cloud system has significant impact on the CTP retrieval. Figure ~~6e~~ 8g and ~~6f~~8h show the baseline and retrieved CTP in B-band respectively, which are similar to, but greater than the A-band. As shown in Figure 8i, the retrieved CTP at EPIC B-band is overall significantly larger than the retrieved CTP at EPIC A-band, which mean difference is up to 200 mb. ~~Because we use the cloud optical depth to estimate the cloud pressure thickness in our retrieval, part of the retrieval error is from the cloud optical depth and the equation for cloud pressure thickness estimation.~~


[a]
A-band Cloud TOP Pressure (baseline)
[b]
200 400 600 800 1000
mb
A-band Retrieved Cloud TOP Pressure
[c]
200 400 600 800 1000
mb
EPIC cloud tau
[d]
10 20 30 40 50
cldtau
B-band Cloud TOP Pressure (baseline)
[e]
200 400 600 800 1000
mb
B-band Retrieved Cloud TOP Pressure
[f]
200 400 600 800 1000
mb

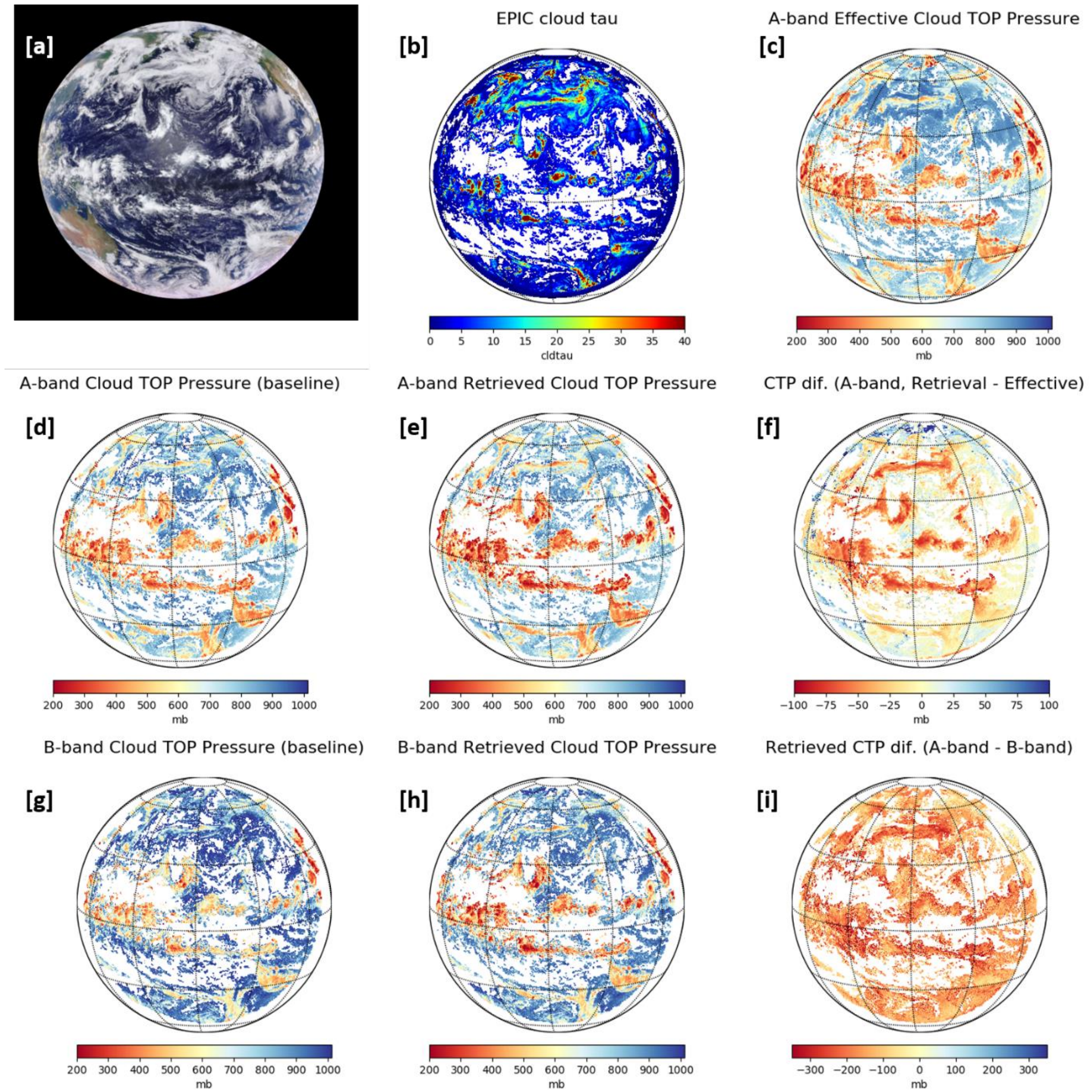


Figure ~~6~~8. (a) RGB image from DSCOVR EPIC measurement at GMT time 00:17:51 on July 25, 2016; (b) and (c) COD (liquid assumption) and A-band effective CTP from NASA ASDC EPIC L2 products; (d) and (e) Baseline and retrieved CTP derived from EPIC A-band measurement~~. (d) Cloud optical depth (liquid assumption) from EPIC L2 products~~; (f) the difference of A-band retrieved CTP and A-band effective CTP; (~~e~~g) and (~~f~~h) Baseline and retrieved CTP derived from EPIC B-band measurement; and (i) the difference of retrieved CTP between EPIC A-band and B-band.

As previously stated in the subsection 3.2: under single-layer cloud situations, the CTPs derived from EPIC A-band measurements have good agreement with the CTP from CALIPSO measurements; under multiple-layer cloud situations, the CTPs derived from EPIC measurements may be larger than the CTPs of high level thin-clouds due to the effect of photon penetration. Therefore, in the global range, for the large scale low-level stratus clouds, the retrieved CTPs from EPIC A-band measurements should agree well with the actual value of

CTPs, but for the complex cloud system with multiple-layer clouds, the CTPs derived from EPIC A-band measurements may be larger than that of high level thin-clouds.

~~2.~~4. Conclusion

The in-cloud photon penetration has significant impacts on the CTP retrieval when using DSCOVR EPIC oxygen A- and B- band measurements. To address this issue, we proposed two methods, (1) the LUT based method and (2) the analytic transfer inverse model method for CTP retrieval with consideration of in-cloud photon penetration. In the analytic transfer inverse model method, we build an analytic equation that represents the reflection at TOA from above cloud, in-cloud, and below-cloud, respectively. The coefficients of this analytic equation can be derived from a series of EPIC simulations under different atmospheric conditions using a non-linear regression algorithm. With EPIC observation data, the related solar zenith and sensor view angle, surface albedo data, ~~cloud optical depth~~COD, and estimated cloud pressure thickness, we can retrieve the CTP by solving the analytic equation.

We developed a package for the DSCOVR EPIC measurement simulation. The high resolution radiation spectrum must be simulated first and then integrated with the EPIC filter function in order to accurately simulate EPIC measurements. Because this process is highly time-consuming, a polynomial fitting function is used when calculating the oxygen absorption coefficients under different atmospheric conditions. At the same time, the double-k approach is applied to do the high-resolution spectrum simulation to further reduce time-costs, which can obtain high accuracy results with hundred-fold time reduction. The results of the EPIC simulation measurements are consistent with theoretical analysis.

Based on the EPIC simulation measurements, we derived a series of coefficients from various solar zenith angles for the analytic EPIC equations. Using these coefficients, we performed CTP retrieval for real EPIC observation data. We have two kinds of retrieval results: baseline CTP and retrieved CTP. The baseline CTP is similar to the effective CTP in ~~Yuekui~~ Yang et al., (~~2012~~2019), which does not consider cloud penetration. The retrieved CTP is derived by solving the analytic equation, with consideration of the in-cloud and below-cloud interactions. Compared to the effective CTP provided by NASA ASDC L2 data, the baseline CTP value at A-band is slightly higher, but the baseline CTP value at B-band is substantially higher. The retrieved CTP for both oxygen A- and B- bands is smaller than the related baseline CTP. At the same time, compared to the oxygen A-band, both baseline CTP and retrieved CTP at oxygen B-band is ~~obviously~~ larger. The cloud layer top pressure from CALIPSO measurements is used to validate the CTP derived from EPIC measurement. Under single-layer cloud situations, the retrieved CTPs for oxygen A-band agree well with the CTPs from CALIPSO, which mean difference is within 5 mb in the case study. Under multiple-layer cloud situations, the CTPs derived from EPIC measurements may be larger than the CTPs of high level thin-clouds due to the effect of photon penetration.

Currently, this analytical transfer model method can only retrieve CTP, and it still need cloud pressure thickness as an input parameter. However, in the satellite observations, both CTP and cloud pressure thickness are unknown. The estimation or assumption of cloud pressure thickness will bring in extra error in CTP retrieval. In the near future, we will do further studiesplan to address this issue.

Acknowledgements and Data

This work was supported partially by NASA's Research Opportunities in Space and Earth Science (ROSES) program element for DSCOVR Earth Science Algorithms managed by Dr. Richard Eckman, by the National Science Foundation (NSF) under contract AGS-1608735; and by the National Oceanic and Atmospheric Administration (NOAA) Educational Partnership Program with Minority Serving Institutions cooperative agreement #NA11SEC4810003. Dataset of DSCOVR EPIC Level 1B can be found in https://eosweb.larc.nasa.gov/project/dscovr/dscovr_epic_l1b_2; dataset of EPIC Level 2 can be found in https://eosweb.larc.nasa.gov/project/dscovr/dscovr_epic_l2_cloud_01; dataset of surface albedo from GOME can be found in http://temis.nl/surface/gome2_ler/databases/; dataset of cloud layer data from CALIPSO can be found in https://eosweb.larc.nasa.gov/project/calipso/cal_lid_l2_05kmclay_standard_v4_20.

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