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Synergistic Use of AIRS and MODIS for Dust Top Height Retrieval over Land

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ABSTRACT

It is nontrivial to extract the dust top height (DTH) accurately from passive instruments over land due to the complexity of the surface conditions. The Moderate Resolution Imaging Spectroradiometer (MODIS) deep blue (DB) algorithm can be used to infer the aerosol optical depth (AOD) over high-reflective surfaces. The Atmospheric Infrared Sounder (AIRS) can simultaneously obtain the DTH and optical depth information. This study focuses on the synergistic use of AIRS observations and MODIS DB results for improving the DTH by using a stable relationship between the AIRS infrared and MODIS DB AODs. A one-dimensional variational (1DVAR) algorithm is applied to extract the DTH from AIRS. Simulation experiments indicate that when the uncertainty of the dust optical depth decreases from 50% to 20%, the improvement of the DTH retrieval accuracy from AIRS reaches 200 m for most of the assumed dust conditions. For two cases over the Taklimakan Desert, the results are compared against Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) measurements. The results confirm that the MODIS DB product could help extract the DTH over land from AIRS.

Key words: AIRS, MODIS, dust height, Cloud-Aerosol Lidar with Orthogonal Polarization

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1. Introduction

Dust aerosol plays a significant role in climate change and global warming (Hansen et al., 1997; Seinfeld et al., 2004; IPCC, 2007). Accurate dust parameters are important for numerical weather prediction and climate change studies. It is also very important to determine the dust top height (DTH) for the study of dust transport, dust sources and deposits. An improvement in the determination of the dust layer height will be helpful for understanding the dust life cycle and to better estimate the long-wave forcing due to dust (IPCC, 2007). However, it is nontrivial to extract the dust optical depth and DTH accurately from passive measurements over land, especially over bright surfaces (Kaufman et al., 2002).

Hyperspectral instruments, such as the Atmospheric Infrared Sounder (AIRS) (Chahine et al., 2006), could be applied to simultaneously extract the dust optical depth and top height over oceans (De Souza-Machado et al., 2006; Peyridieu et al., 2010) and over land (Yao et al., 2012; Han and Sohn, 2013). However, the retrieval of dust properties (e.g., optical depth) from thermal radiance measurements relies on the background temperature, aerosol layer height, dust loading and temperature profile. Consequently, DTH retrieval from hyperspectral infrared radiances depends on the accuracy of other parameters. Additionally, although observations in short-wave IR channels are also sensitive to the above two parameters, they are affected by the strong reflected solar radiation in the daytime. As a result, only observations in the long-wave band are used to retrieve the two parameters. Therefore, more information is needed for dust height retrieval improvement due to the ill-posedness of the retrieval problem. For example, if the optical depth obtained from other measurements is used to constrain the initial guesses of dust property retrievals, the DTH from AIRS should be improved.

In the past few decades, other techniques have been developed to infer the dust optical depth from satellite-based instruments (Hsu et al., 2004; Sokolik, 2004; Torres et al., 2007; Winker et al., 2007). The Moderate Resolution Imaging Spectroradiometer (MODIS) Deep Blue (DB) algorithm has been used to infer the aerosol optical depth (AOD) over land. One advantage of this algorithm is that it is not very sensitive to the aerosol height (Hsu et al., 2004). As a result, it would appear that the MODIS DB AOD could provide some useful information for DTH retrieval from hyperspectral infrared data. In other words, if the optical depth derived from MODIS is used as the initial guess in a one-dimensional variational (1DVAR) retrieval, the uncertainty of the DTH retrieved from AIRS could be reduced. A good correlation

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between the thermal infrared optical depth from AIRS and the MODIS optical depth for a dust storm spreading over the eastern Mediterranean has been presented by De Souza-Machado et al. (2006). However, there are significant differences between the infrared and visible optical depth due to the different absorption and scattering properties of the dust particles in the two wave bands. In other words, the visible AOD could not be directly used as the initial guess for AIRS retrievals. Fortunately, a stable relationship between AIRS infrared and MODIS DB AODs was found for several single layer dust storms (Yao et al., 2012). As a result, the infrared AOD can be estimated from the visible AOD using this relationship.

The aim of this paper is to present the utility of combining AIRS radiance observations and the MODIS DB AOD product with a 1DVAR algorithm for improving the accuracy of DTH retrieval. First, a simulation study is presented to show the possible improvement of DTH retrievals by the synergistic use of MODIS and AIRS. Then, the real DTH retrievals from combined MODIS DB AOD and AIRS infrared radiance measurements over the Taklimakan Desert are evaluated against Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) measurements. Simulation experiments and a two-case analysis indicate that the MODIS DB could help extract the DTH over land from AIRS.

2. Data

2.1. *AIRS*

The AIRS instrument, which was launched in 2002 by NASA on the Earth Observing System (EOS) Aqua satellite, is a hyperspectral infrared sounder that includes 2378 channels covering the 3.74–4.61 μm, 6.20–8.22 μm and 8.8–15.4 μm wavebands (Chahine et al., 2006). Each cross-track scan contains 90 footprints on the ground with a horizontal resolution of about 13.5 km at nadir and a scan swath of 1600 km (Aumann and Miller, 1994). There are 240 granules available over 24 hours, each of which includes 135 scans. Although its primary purpose is to derive atmospheric temperature and humidity profiles, it has been used to infer cloud properties (Li et al., 2005) and dust properties over oceans (Pierangelo et al., 2004; De Souza-Machado et al., 2006; Peyridieu et al., 2010; De Souza-Machado et al., 2010) and over land (Yao et al., 2012; Han and Sohn, 2013).

2.2. *MODIS*

The MODIS instrument with AIRS onboard the same Aqua satellite can be used to retrieve the AOD over land. The MODIS DB algorithm is sensitive to aerosols over brightly reflecting source regions, as it uses blue channels due to their relatively lower surface reflectance (Hsu et al., 2004). It is indicated that the resulting AOD error is less than 5% at 550 nm in the case of an error of 2 km in the aerosol plume altitude (Hsu et al., 2006). By comparison with Aerosol Robotic Network (AERONET) observations in East Asia, the MODIS DB product uncertainty is about 20%–30% (Hsu et al., 2006). The MODIS DB product has been validated by the AOD results from the ground-based sun photometer measurements at Tazhong (39.00°N, 83.40°E) and Hotan (37.08°N, 79.56°E) in the Taklimakan Desert during 2002–03 (Li et al., 2012). It is shown that the correlation coefficients between the results from the two techniques are 0.94 and 0.96 at the two sites, respectively.

3. Retrieval methodology

Different methods have been developed for inferring the dust parameters from AIRS. A look-up-table-based approach has been developed to obtain the dust height and infrared optical depth over the Atlantic Ocean from AIRS measurements (Pierangelo et al., 2004; Peyridieu et al., 2010). A physical retrieval algorithm (De Souza-Machado et al., 2010) has been developed to derive the dust AOD and altitude in the Mediterranean from the AIRS long-wave infrared data. However, simultaneous retrieval of the DTH and optical depth over land is more difficult, due to the great uncertainty of bright surface emission. Yao et al. (2012) firstly simultaneously obtained the DTH and infrared optical depth from AIRS over land by developing a 1DVAR algorithm with the baseline fit (BLF) infrared emissivity dataset (Seemann et al., 2008) and atmospheric parameters from ECMWF as the inputs for the forward model. Then, Han and Sohn (2013) further examined the capability of retrieving the DTH and infrared optical depth over land from AIRS using a statistical artificial neural network approach. The advantage of the 1DVAR algorithm is that it can easily include more inputs in the retrieval and simultaneously takes into account uncertainties in the radiative transfer model, instrument measurement and other effects in the inverse process. This retrieval method has been used to infer cloud parameters by combining AIRS and MODIS by Li et al. (2004, 2005).

By taking into account the different characteristics of each satellite, a synergy of multi-sensor dust information should be an effective way to create more accurate dust properties. A stable connection between the infrared and DB AODs was found by Yao et al. (2012) for several single layer dust storms over the Taklimakan Desert, which is a major source of dust storms in East Asia. This relationship paves the way for the possible improvement of dust altitude retrieval by using the infrared AOD estimated from the MODIS visible AOD over this area. In this study, the thermal optical depth is first estimated from MODIS DB results using the stable relationship. The thermal optical depth is then used as an input in the 1DVAR algorithm for improving the DTH from AIRS.

The general idea of the 1DVAR theory is to minimize a cost function $J(\boldsymbol{X})$ with respect to the unknown state $\boldsymbol{X}$, which measures the degree of fit of the dust measurements to the background statistical constraints and, optionally, other observational and physical constraints. In general, the 1DVAR solution is obtained by minimizing the following cost function (Rodgers, 1976):

$$J(\boldsymbol{X}) = (\boldsymbol{X}-\boldsymbol{X}_{\rm a})^{\rm T}\boldsymbol{S}_{\rm a}^{-1}(\boldsymbol{X}-\boldsymbol{X}_{\rm a}) + [\boldsymbol{Y}_{\rm m}-\boldsymbol{F}(\boldsymbol{X})]^{\rm T}\boldsymbol{S}_{\varepsilon}^{-1}[\boldsymbol{Y}_{\rm m}-\boldsymbol{F}(\boldsymbol{X})] , \quad (1)$$

where $\boldsymbol{X}_{\rm a}$ is the background state with the assumed background error covariance matrix $\boldsymbol{S}_{\rm a}$ that constrains the solution; $\boldsymbol{Y}_{\rm m}$ is an observation vector representing the measured AIRS brightness temperatures (BTs); $\boldsymbol{F}(\boldsymbol{X})$ is a forward radiative transfer model (RTM) with $\boldsymbol{X}$ as its input; and $\boldsymbol{S}_{\varepsilon}$ is the observation error covariance matrix, which includes instrument noise plus the assumed forward model error. It is assumed that the error distribution for both $\boldsymbol{X}$ and $\boldsymbol{Y}_{\rm m}$ is Gaussian with zero mean and that the background and observation error is uncorrelated. The equation is numerically solved by a quasi-Newtonian iteration (Eyre, 1989):

$$\delta\hat{\boldsymbol{X}}_{n+1} = (\boldsymbol{K}_n^{\rm T}\boldsymbol{S}_{\varepsilon}^{-1}\cdot\boldsymbol{K}_n+\boldsymbol{S}_{\rm a}^{-1})^{-1}\cdot\boldsymbol{K}_n^{\rm T}\boldsymbol{S}_{\varepsilon}^{-1}\cdot(\delta\boldsymbol{Y}_n+\boldsymbol{K}_n\cdot\delta\hat{\boldsymbol{X}}_n) , \quad (2)$$

where $\delta\hat{\boldsymbol{X}}_n=\hat{\boldsymbol{X}}_n-\boldsymbol{X}_{\rm a}, \delta\boldsymbol{Y}_n=\boldsymbol{Y}_n-\boldsymbol{Y}(\hat{\boldsymbol{X}}_n)$, and $\boldsymbol{K}=\partial\boldsymbol{F}/\partial\hat{\boldsymbol{X}}$ represents the linear or tangent model of the forward model $\boldsymbol{F}$, which is applied to calculate satellite observations with the input $\boldsymbol{X}$.

In the retrieval, the vector $\boldsymbol{X}$ containing only the DTH and dust density number (directly related to the optical depth) needs to be solved. Other parameters, such as atmospheric vertical profiles as inputs for the forward model calculation, are assumed to be known. The vector $\boldsymbol{Y}(\hat{\boldsymbol{X}}_n)$ is the simulated AIRS BTs from a dust state $\boldsymbol{X}_n$ with a forward transfer model. The superscripts n and $n+1$ represent the iteration number. $\hat{\boldsymbol{X}}$ represents an estimated value of $\boldsymbol{X}$. The solution is obtained when $\delta\boldsymbol{Y}_n$ is less than 0.5 K or the $\delta\boldsymbol{Y}_n$ difference from two successive iterations is less than 0.005 K.

To make the retrieval process stable, the geometrical depth of dust is assumed to be five layers in the forward model, which is around 1 km in the lower troposphere. The initial density number is set to 2000 with an uncertainty of 2000. The dust optical depth with the above conditions is about 1 in the long-wave infrared band. The initial dust top is set to be the logarithm of 617 hPa with an uncertainty of 0.1. The observation error from the RTM uncertainty, instrument noise and calibration uncertainty is set to 0.5 K for each used channel. These settings are similar to those in the paper presented by Yao et al. (2012).

In the physical iterative retrieval, the eight AIRS channels between 870 and 973 cm^{-1} are used. The radiative transfer for (A)TOVS (RTTOV 9.3) is applied to calculate the AIRS radiances in the presence of dust. The model can be used to rapidly simulate radiances for the AIRS instrument given surface and atmospheric parameters. This model including a multiple scattering code allows simulation of infrared radiances in cases of dust skies. This model has been used by Han et al. (2012) to compare the calculated radiances to the AIRS measurements under dust sky conditions from January 2008 to December 2009. The mineral dust absorption and scattering coefficients are calculated by combining particle size measurements from a nine-year ground observation dataset (Han et al., 2012) from the Dunhuang Skynet station, which is located to the east of the Taklimakan Desert, and the Optical Properties of Aerosols and Clouds (OPAC) dataset of optical properties (Hess et al., 1998). The atmospheric profiles and surface temperature are obtained from European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis data. Additionally, the surface infrared emissivity spectrum for the satellite observation simulations is taken from the baseline fit (BLF) emissivity datasets developed by the University of Wisconsin-Madison (Seemann et al., 2008). For more details on this algorithm, see Yao et al. (2012).

4. Simulation analysis

To demonstrate the potential of the AIRS channels for retrieving DTH and AOD simultaneously, the sensitivity of AIRS BTs to DTH and AOD for various DTH and AOD values is analyzed. The assumed dust layer thickness is about 1 km in the simulation analysis. The results for the channel at 10.4 μm are presented in Fig. 1. Sensitivity to AOD corresponds to a variation of 0.1 around the given AOD value for a given DTH. The sensitivity of DTH corresponds to a variation of 0.5 km around the given DTH value for a given AOD. This figure indicates that the reliable AOD values are retrieved

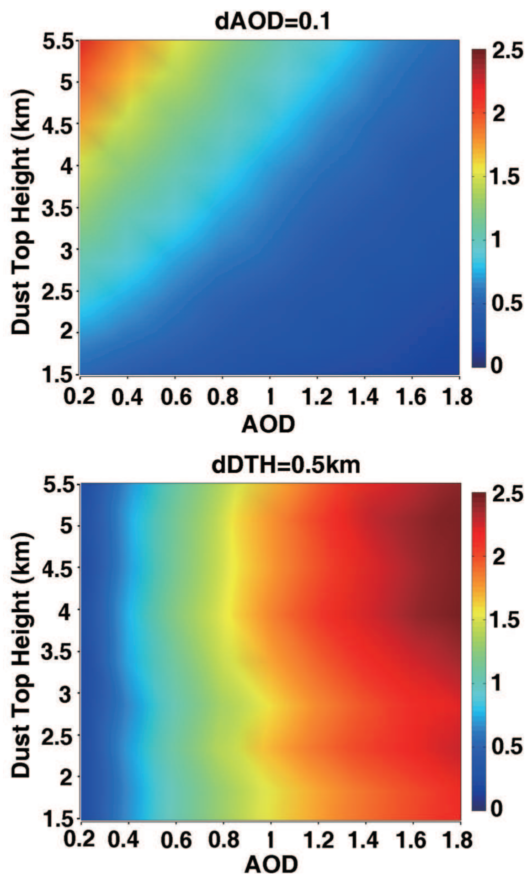

Fig. 1. Sensitivity of the channel at 10.4 μm to AOD for different DTHs (upper: BT variation corresponds to a variation of 0.1 around the given AOD value for a given DTH), and to DTH for different AODs (bottom: BT variation corresponds to a variation of 0.5 km around the given DTH value for a given AOD).

for AOD values between 0.1 and 1.2 and DTH values greater than 2 km. The sensitivity of AIRS to the AOD increases with increasing DTH; and the observation is very sensitive to the DTH for the AOD greater than 0.2. The sensitivity of AIRS to the DTH increases with increasing AOD. Overall, the results illustrate that the AOD information is very important for the retrieval of the DTH when the AOD value is less than 1.

To analyze the impact of the uncertainty of the initial dust AOD on the DTH retrieval, simulation experiments for various conditions are conducted. In the simulation, the DTH is in the range 1.5–6 km and the AOD varies from 0.1 to 2. The uncertainty of the model simulation and the observation is set to 0.5 K. The initial value of the DTH is set to 4 km and the initial AOD is the actual value but with an uncertainty of 50% or 20%, respectively, in the experiments. Figure 2 shows the retrieval bias as a function of the DTH and dust AOD for the two different uncertainties of the initial dust AOD.

It is noted that when the uncertainty of the AOD guess is 50%, the retrieval error of DTH is greater than 0.5 km when the DTH is less than 2.5 km and the AOD is less than 0.5. The DTH is overestimated by 1.5 km when the DTH is 1.5 km and it is underestimated by 1.0 km when the DTH is 6 km. However, when the uncertainty of the AOD guess is 20%, the error decreases in the above situations. The retrieval error of the DTH is less than 0.5 km when the DTH is greater than 2.0 km and the AOD is greater than 0.5. Figure 2c indicates that the improvement is approximately, or greater than, 0.2 km when the DTH is greater than 4.5 km or less than 2.5 km. This confirms that accurate AOD information could contribute greatly to the improvement of DTH retrievals. Additionally, the impact of the AOD uncertainty on the DTH retrieval is less for the optically thick dust than that for the relatively light dust, which is consistent with the results illustrated in Fig. 1.

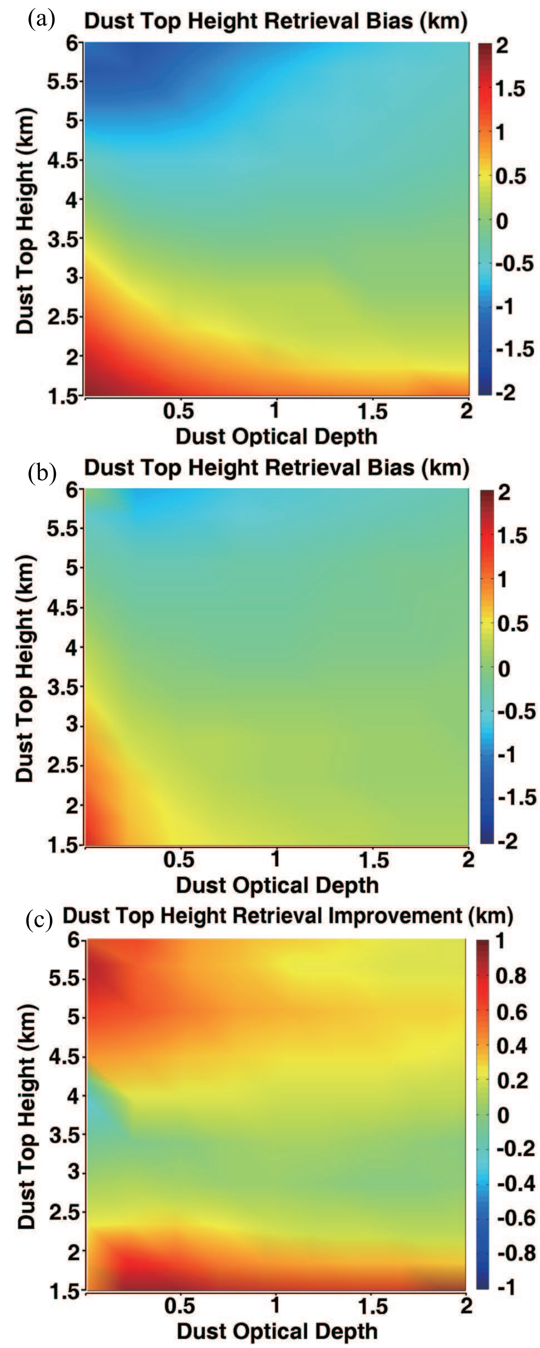

Fig. 2. DTH retrieval error as a function of dust optical depth and DTH with initial AOD uncertainty of 50% (upper) and 20% (middle). The bottom panel is the difference between the absolute values of the upper and middle panels.

5. Application to AIRS/MODIS

The non-linear regression equation

$$AOD_{IR} = -0.492 \times [1 - \exp(0.479 \times AOD_{vis})] , \quad (3)$$

which is derived from the dust storm on 13 March 2006 presented by Yao et al. (2012), is used in the retrievals for the cases on 8 April and 10 May 2007 in this study. AOD_{IR} represents the AIRS infrared AOD and AOD_{vis} indicates the MODIS DB AOD. The dust storm on 13 March 2006 was very heavy, which means the retrievals are less affected by the surface conditions. As a result, this equation could reasonably represent the relationship between the longwave infrared and DB AOD values. To investigate the possible improvement of the DTH retrieval, the retrieved DTHs from the combination experiments are examined for the two dust storms. These two dust storms used for evaluation were relatively light, as shown by Yao et al. (2012). In the combination retrieval experiments, the infrared AOD derived from the MODIS DB AOD using Eq. (3) is used as the initial guess and its uncertainty is set to 20%. Although the infrared AOD is not the input for the forward model, it is directly dependent on the density number. As a result, the infrared AOD can easily be converted to the density number as the input for the forward model.

The retrieval experiments indicate that the DTH retrievals over some areas are unreasonable when the surface temperature from ECMWF is fixed in the retrieval process. For most of the areas, the DTH is underestimated by comparison with the active measurements, which is likely caused by the underestimation of the assumed surface temperature. For the surface temperature uncertainties of 2 K and 5 K, the retrieved DTHs are also investigated. The experiments show that the final results agree significantly better with the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) observations when the uncertainty of the surface temperature is set to 5 K, which indicates that the DTH retrieval is considerably affected by the uncertainty of the surface temperature. Additionally, the study by Yao et al. (2012) shows that dust property retrievals could be affected by the uncertainty assumption of the surface temperature, especially for relatively light dust. In the following study, the uncertainty of the surface temperature is set to 5 K.

To show improvement in different regions, satellite images of the DTH with and without MODIS AOD are presented in Fig. 3. From this figure, it seems that the DTH retrievals from AIRS with MODIS could obtain a smoother distribution pattern than without MOIDS. For the dust storm on 8 April 2007, some noise in the DTH values from the east to the west desert without MODIS are reduced by combining MODIS with AIRS. Dusty regions indicate heights of 3 to 4 km, whereas the elevated cloud in the upper left of this scene is shown in white. For the second case, a similar improvement is also presented. From the center of the desert to the right, the DTHs gradually change from 2.5 km to 3.5 km.

In Fig. 4, the retrieved DTHs along the CALIPSO satellite track shown in Fig. 3 are indicated by the dashed line. The vertical cross section from CALIOP along the track is also shown. The CALIOP observations are presented by the color bar presenting the backscatter (km^{-1} sr^{-1}) times 1000. The solid black line represents the surface level. For clarity, CALIOP backscatter values less than 0.75×10^{-3} km^{-1} sr^{-1} are masked. For comparison, the results without DB AOD are also presented in this figure. The comparison shows that when the MODIS DB AOD is used, the variation of height agrees better with the lidar. For the first case, the retrieved DTHs in the cross sections from 39.2° to 40.3°N improve by about 500 m. For the second case, the retrieved values from 38° to 40°N vary gradually and capture the variation pattern more reasonably. This improvement suggests that the MODIS DB AOD could help the retrieval of DTH from AIRS.

An experiment with the dust infrared AOD derived from MODIS DB AOD as the true values in the retrieval is also conducted. However, the result shows that the retrieved DTH is worse. This means that the derived infrared AOD from the MODIS DB AOD could not be used as the true value. On one hand, the MODIS DB AOD should have an uncertainty to some extent; on the other hand, the relation between the MODIS DB AOD and the Thermal InfraRed TIR AOD has some uncertainties because they reflect different optical characteristics of the dust.

It is noted that the DTH retrievals on the left of 38.6° latitude in Fig. 3 do not agree well with CALIPSO. A possible explanation for this is that the surface conditions are more complicated between the desert and the mountain, where a river flows. The surface emissivity may be underestimated, which leads to the underestimation of the DTH. The temperature profile from ECMWF may also not be accurate enough over that area.

6. Summary

Due to strong surface radiation and its variation, as well as the radiative transparency of the dust layer, it is challeng-

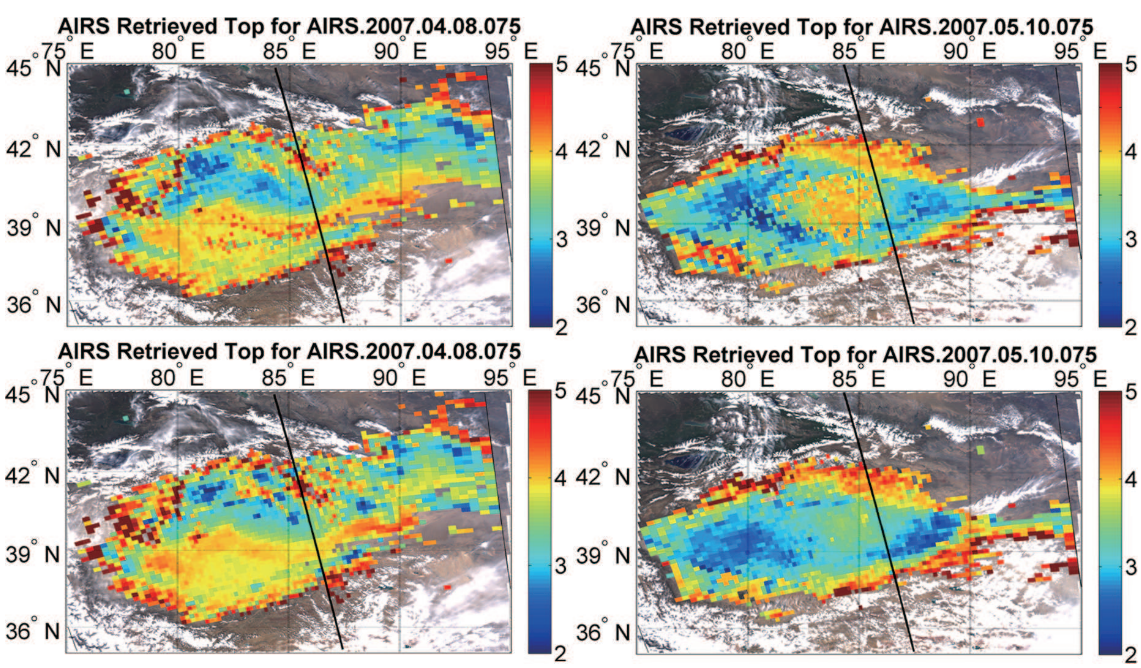

Fig. 3. AIRS-retrieved DTH (left: 8 April 2007; right: 10 May 2007) for a surface temperature uncertainty of 5 K (upper: without MODIS; bottom: with MODIS). Black line is the CALIPSO track.

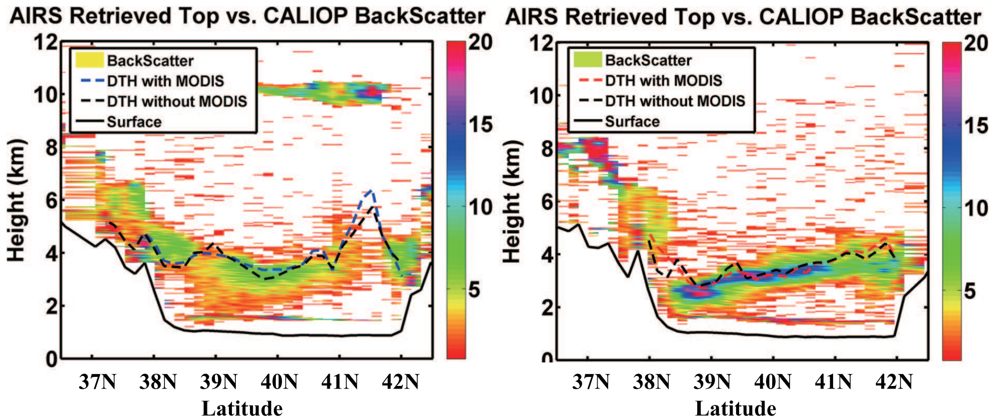

Fig. 4. DTH retrievals (left: 8 April 2007; right: 10 May 2007) from AIRS with and without MODIS DB for a surface temperature uncertainty of 5 K compared with CALIPSO observations.

ing to infer DTH from AIRS over land. Simulation analysis shows that the addition of dust AOD could decrease the error of the DTH retrieval. Because the MODIS DB algorithm can retrieve the AOD over bright surfaces and a stable relationship between its products and the AIRS infrared AOD is reported over the Taklimakan Desert, the MODIS DB AOD is combined with AIRS to help the DTH retrievals over this area using the 1DVAR algorithm. For two cases over the Taklimakan Desert, the results are compared against CALIOP measurements. The results show that MODIS DB could improve the DTH over land from AIRS.

In theory, the method could be applied to dust storms in the Gobi Desert and eastern China if an accurate forward model is available. It is well known that the performance of satellite-based dust properties over land is critically dependent on the accuracy of the forward model. However, the size distribution of Asian dust only at Dunhuang located in the east of the Taklimakan Desert was obtained from sky radiometer measurements, and the model based on the size distribution was validated by Han et al. (2012). Away from this region, dust composition may undergo changes because dust particles have a tendency to be mixed with other aerosol species and some particles tend to sink during transport. Consequently, only the dust storm cases over the Taklimakan Desert are used to examine the synergistic use of AIRS and MODIS for DTH retrieval over land in this study. If the dust composition and optical properties over other areas are available, the forward model could be further validated and then the retrieval method investigated.

Additionally, it should be noted that the retrieval uncertainty depends on the accuracy of the surface and atmospheric state. The retrieval will be more complicated for multi-layered dust. In theory, the sensitivity of the observation to the lower dust layer decreases with the increase of the optical thickness of the upper dust layer. The simulation shows that the observation is not sensitive to AOD while the infrared AOD is greater than 1. To evaluate the retrievals simply and robustly, we only examine cases for which an extensive single aerosol layer is detected and measured by the lidar. In northwestern China, the single layer dust is dominant according to the available cases in 2007–08, although more cases will be analyzed in the near future.

Combining measurements from different instruments is one of the most important areas in the application of satellite remote sensing data. This study demonstrates the capability of combining MODIS and the hyperspectral infrared instrument to extract more accurate dust parameters. In the future, the DTH climatology dataset with AIRS and MODIS products from 2002 will be developed. Additionally, this technique will be relevant to data from the Visible Infrared Imaging Radiometer Suite (VIIRS) and Cross-track Infrared Sounder (CrIS) on the Suomi National Polar-orbiting Partnership (Suomi NPP) and future Joint Polar Satellite System (JPSS). It also demonstrates the potential for retrieving the Asian DTH by combining imager and hyperspectral infrared measurements on the FengYun-4 series, which will be launched in 2016.

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