Remote Sensing Estimation of Atmospheric Longwave Radiation in the Heihe River Basin under Dust Weather Conditions

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Abstract

Due to the complexity of scattering and absorption mechanisms of dust aerosols, no mature retrieval algorithm for atmospheric longwave radiation applicable to dust storm conditions currently exists. Based on a comparative analysis of the impacts of typical dust, urban, rural, and marine aerosols on atmospheric longwave radiation forcing and MO DIS channel radiance, we propose modifying a linear model using aerosol optical parameters to construct an atmospheric longwave radiation estimation model suitable for dust aerosol conditions, and validate the model's performance using measured data from four observation stations in the Heihe River Basin (Huazhaizi Desert Station, Mixed Forest Station, Heihe Remote Sensing Station, and Zhangye Wetland Station). The results indicate that the root mean square error of remotely sensed atmospheric longwave radiation at the four stations ranges from 17.1~20.4 W · m-2, with biases ranging from -12.3~-1.8 W · m-2. By accounting for variations in dust aerosol optical thickness and radiation forcing effects, the modified model can significantly improve the retrieval accuracy of atmospheric downward radiation under the influence of dust aerosols, reduce uncertainties in longwave radiation applications, and provide an important reference for surface energy budget studies in arid regions.

Full Text

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Remote Sensing Estimation of Atmospheric Longwave Radiation Under Dust Weather Conditions in the Heihe River Basin

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Abstract: Due to the complexity of dust aerosol scattering and absorption mechanisms, there is currently no mature retrieval algorithm for atmospheric longwave radiation applicable to dust weather conditions. Based on a comparative analysis of the effects of common dust, urban, rural, and marine aerosols on atmospheric longwave radiative forcing and channel radiance, this study proposes modifying a linear model using aerosol optical parameters. An atmospheric longwave radiation estimation model suitable for dust aerosol conditions was constructed, and its applicability was evaluated using measured data from four observation stations in the Heihe River Basin (Huazhaizi Desert Station, Mixed Forest Station, Heihe Remote Sensing Station, and Zhangye Wetland Station). The results show that the root mean square error of remotely sensed atmospheric longwave radiation at the four stations is 17.1–20.4 $\mathrm{W \cdot m^{-2}}$, with a bias of –12.3 to –1.8 $\mathrm{W \cdot m^{-2}}$. By accounting for variations in dust aerosol optical depth and radiative forcing effects, the modified model can significantly improve the retrieval accuracy of atmospheric downward radiation under dust aerosol influence, reduce uncertainties in longwave radiation applications, and provide an important reference for studying surface energy budgets in arid regions.

Keywords: atmospheric longwave radiation; dust aerosol; radiative forcing; MODIS; Heihe River Basin

Downward surface longwave radiation (DSLR) is a critical indicator of energy exchange in the Earth-atmosphere system, representing the contribution of the entire atmospheric column to downward radiation. Statistical relationship models can be established between DSLR and sensor radiance data [1]. This approach has a physical basis, is simple and efficient, offers high algorithm stability, and is suitable for operational remote sensing data products, but it does not consider the effects of clouds and aerosol types on the model.

Dust aerosol serves as an important radiative forcing factor, accounting for more than half of the total tropospheric aerosol mass [2]. Estimating longwave radiation under dust aerosol conditions is a challenging task, with the complexity of dust optical properties and radiative transfer mechanisms being the primary sources of error.

In recent years, numerous scholars have conducted research on dust aerosol. Ru Jianbo et al. [3] attempted to extract dust aerosol extinction coefficients from the total backscatter coefficient of aerosols. Xie Yanqing [4], Jia Chen et al. [5], and Wang Lianxia et al. [6] carried out studies on retrieving aerosol optical depth and single scattering albedo using satellite sensors including Landsat 8, FY-4A VIIRS, and S5P/TROPOMI. Li Ding et al. [7] used portable sun photometers to measure dust aerosol optical depth and asymmetry parameters in four desert and semi-desert regions of northwestern China, finding strong seasonal variations in their optical and radiative properties, with aerosol AOD accounting for more than half of the total tropospheric aerosol content. Tian Lei et al. [8] used ground-based observation data to calculate and analyze the effects of dust aerosol on atmospheric counter-radiation, finding that when atmospheric turbidity is less than 3.85, atmospheric counter-radiation increases with turbidity, but shows an opposite trend beyond this critical value. Sicard et al. [9] investigated the longwave radiative forcing of dust aerosol based on radiative transfer models, revealing high sensitivity to dust particle radius, refractive index, distribution state, and surface temperature. Previous research has focused on quantitative extraction of dust aerosol parameters and description/analysis of their radiative effects, with few studies on DSLR remote sensing estimation under dust aerosol conditions.

Therefore, this study analyzes the effects of dust aerosol variations on MODIS TOA channel radiances under different surface parameter and atmospheric profile scenarios, establishes a statistical relationship model between DSLR and TOA using radiative transfer simulation data, develops a new DSLR estimation method, and finally validates the model and evaluates its universality using ground-based measurement data from the Heihe River Basin, aiming to improve the accuracy of DSLR remote sensing retrieval under dust aerosol conditions and provide a reference for related research.

1.1 Study Area Overview

This study selects the Heihe River Basin as the research area, located between 98°–102°E and 38°–42°N, covering an area of approximately 1.429$×10^{5}$ km^2. The upper, middle, and lower reaches of the Heihe River Basin encompass various land surface types including grassland, farmland, and wetland, making it an important base for terrestrial river research in China. Numerous scientific research experiments have been conducted in this region [21], accumulating a wealth of hydrometeorological observation network data, which not only provides a solid scientific data foundation for watershed eco-hydrological research but also supports the development of dust aerosol models in this study. The study area extent and site distribution are shown in Figure 1 [Figure 1: see original paper].

1.2 Data

1.2.1 Simulated Data Considering that atmospheric temperature, humidity, wind, and aerosol parameters are dynamically changing, making it difficult to achieve synchronization between ground measurements and satellite observations, this study utilizes datasets produced by the MODTRAN radiative transfer model to analyze and evaluate the effects of dust aerosol on atmospheric longwave radiation and MODIS remote sensing. Atmospheric profiles were obtained from the Thermodynamic Initial Guess Retrieval (TIGR) database, with each profile containing 26 layers of temperature, humidity, pressure, and elevation information. Accounting for both clear-sky and dust outbreak scenarios, 235 clear-sky atmospheric profiles were selected using relative humidity and continuous humidity as screening criteria, with atmospheric water vapor content (WVC) ranging from 0.05 to 6.15 $\mathrm{g \cdot cm^{-2}}$ and bottom-layer profile temperatures from 235 to 314 K, basically covering the common profile types across four seasons in the study area. Emissivity data were obtained from the ASTER surface emissivity library, and 33 land cover types were selected for simulation based on the characteristics of land surface cover types in the Heihe River Basin. The radiative effects of aerosols depend on their spatial distribution, physical and chemical properties (including particle size, size distribution, chemical composition, etc.), and optical characteristics (such as optical depth and single scattering albedo). Corresponding information for dust aerosol was extracted from the parameter library of the Optical Properties of Aerosols and Clouds (OPAC) software [22]. To enhance universality, surface temperature was varied within a certain range based on the bottom-layer atmospheric temperature, with a variation range of -5 to 15 K.

1.2.2 Remote Sensing Data This study utilizes MODIS data products to validate the feasibility of the model, with sampling time points from January 2018 to December 2019. Six primary products are used: the top-of-atmosphere radiance product MYD021KM, the geolocation product MYD03, the cloud mask product MYD35_{L2}, the water vapor data product MYD05_{L2}, the surface temperature and emissivity product MYD11_{L2}, and the aerosol product MYD04 (C6.1). MODIS AOD does not change significantly within a short period, so this value approximately represents the AOD corresponding to the observation station pixel. To eliminate cloud effects, only clear-sky data are selected in this study. To ensure that selected pixels meet requirements, only pixels identified as clear-sky by the MODIS cloud mask data are chosen. Additionally, a determination is made as to whether aerosols are present in the pixel, and the central pixel at the station location and surrounding pixels with aerosols are selected as target pixels that meet the requirements.

1.2.3 Site Data This study selects site data from the Heihe River Basin from January 2018 to December 2019 to validate the model. Data were obtained from the Heihe Watershed Allied Telemetry Experimental Research (HiWATER) sites provided by the National Tibetan Plateau Data Center [23], including four meteorological stations with different underlying surfaces: Huazhaizi Desert Station, Mixed Forest Station, Heihe Remote Sensing Station, and Zhangye Wetland Station (Table 1). The data were collected by ground radiometers every 10 minutes, and values corresponding to the satellite overpass time were obtained through bilinear interpolation of measurements taken 15 minutes before and after the overpass. Since MODIS data do not change significantly within a short period, this value approximately represents the measurement corresponding to the MODIS pixel. To ensure data validity, at least three valid pixels must surround the station pixel during the matching process. Temporally, ground station data were obtained by bilinearly interpolating measurements taken 15 minutes before and after the satellite overpass to derive values at the satellite overpass time.

1.3 Methods

1.3.1 Near-surface Atmospheric Longwave Radiation Linear Model Algorithm Tang et al. [10] established a hybrid model method for atmospheric longwave radiation estimation based on an algebraic relationship between transmittance and pressure as a channel weighting function to describe the contribution of each atmospheric layer to downward longwave radiation. This algorithm has a clear mechanism, can compensate for deficiencies in physical models caused by overly complex radiative transfer processes or difficulty in obtaining atmospheric input data, and directly utilizes MODIS channel radiance to estimate DSLR. The algorithm offers high computational efficiency, good stability, and robustness, making it suitable for operational applications [11]. The model takes the form:

$$DSLRC = a_0 + a_{1L_{27}} + a_{2L_{28}} + a_{3L_{29}} + a_{4L_{31}} + a_{5L_{32}} + a_{6L_{33}} + a_{7Z}$$

where $DSLRC$ is the estimated downward surface longwave radiation under clear-sky conditions; L_{27}–L_{33} are the TOA radiances measured by MODIS thermal infrared channels; Z is surface elevation; and a_0–a_7 are regression coefficients. This model can explain more than 90% of the variation in atmospheric longwave radiation data, with a standard error of approximately 16 $\mathrm{W \cdot m^{-2}}$ under clear-sky conditions. However, it is mainly applied to clear-sky atmospheric environments with stable aerosol types and low aerosol content, and its applicability in dust aerosol weather conditions has not yet been tested. The changes in MODIS TOA channel radiance under dust aerosol conditions are shown in Figure 3 [Figure 3: see original paper].

1.3.2 Algorithm Correction Approach The difficulty in DSLR remote sensing estimation under dust weather conditions lies in quantifying the longwave radiative forcing of aerosols on the atmosphere and the changes in channel TOA radiance caused by aerosol variations. To investigate the longwave radiative effects of dust aerosol, this study first analyzes the radiative forcing effects caused by four different aerosol types. Based on this analysis, MODIS channel TOA radiance correction and coefficient optimization are performed using aerosol optical depth (AOD) to construct a near-surface atmospheric longwave radiation remote sensing model for dust aerosol conditions.

Figure 2 [Figure 2: see original paper] shows the relationship between the mean bias and standard deviation (STD) of aerosol longwave radiative forcing (ALRF) and AOD for four aerosol types: dust, rural, urban, and marine. The results indicate that ALRF and its STD for all four aerosol types increase with AOD, with an approximately linear relationship between ALRF and AOD. Marine aerosol exhibits the smallest ALRF (1.1 $\mathrm{W \cdot m^{-2}}$ at AOD=1.0), while dust aerosol shows the largest ALRF (3.85 $\mathrm{W \cdot m^{-2}}$ at AOD=1.0) and the largest STD.

Figure 3 illustrates the TOA channel radiance change rate and STD under different AOD conditions for dust aerosol. The radiance change rates for the four surface temperature channels are relatively small, but channels 29, 31, and 32 show relatively larger rates of 3.14%, 3.32%, and 3.51%, respectively. This demonstrates that using AOD for radiance correction and coefficient calibration is feasible when modifying the model for DSLR estimation under dust aerosol conditions.

Based on this, the near-surface atmospheric longwave radiation remote sensing model for dust aerosol conditions (DSLRA) takes the form:

$$DSLRA = a_0 + a_1(b_0 \times AOD + 1)L_{27} + a_2(b_1 \times AOD + 1)L_{28} + a_{3L_{29}} + a_4(b_2 \times AOD + 1)L_{31} + a_{5L_{32}} + a_{6L_{33}} + a_{7Z}$$

where $DSLRA$ is the estimated downward surface longwave radiation under dust aerosol conditions; AOD is aerosol optical depth; and b_0–b_2 are coefficients. To make the algorithm more representative and reduce errors inherent in input parameters, a method of setting partially overlapping intervals adjacent to AOD ranges and grouping them for refinement is adopted to optimize coefficients. The VZA groups are: 33.56°, 44.42°, 51.32°, 56.25°, 60.00°. The WVC groups are: 0.0–1.0, 0.5–1.5, 1.0–2.0, 1.5–2.5, 2.0–3.0, 2.5–3.5, 3.5–4.5, 4.0–5.0, 4.5–5.5, 5.0–6.0, 5.5–6.5 $\mathrm{g \cdot cm^{-2}}$. The AOD groups are: 0.0–0.4, 0.3–0.7, 0.5–1.0, 0.7–1.5, 1.0–2.0, 1.5–2.5, 2.0–3.0, 2.5–3.5, 3.0–4.0, 3.5–4.5, 4.0–5.0, 4.5–5.5, 5.0–6.0, 5.5–6.5. According to the above grouping, 13 sets of coefficients were regressed using the least squares method. The overall flowchart of algorithm construction is shown in Figure 4 [Figure 4: see original paper].

2.1 Sensitivity Analysis

To evaluate the DSLR retrieval errors caused by uncertainties in input variables, a sensitivity analysis of the model is required. Model errors are primarily determined by uncertainties in radiance L and AOD, as well as inherent model errors. The total model error $e(\Delta DSLR)$ can be expressed as:

$$e(\Delta DSLR) = \Delta DSLR(L) + \Delta DSLR(AOD) + \Delta DSLR(alg)$$

where $\Delta DSLR(L)$ and $\Delta DSLR(AOD)$ are the DSLR errors caused by uncertainties in radiance L and AOD, respectively; $\Delta DSLR(alg)$ is the inherent model error; a_i is the coefficient corresponding to the i-th channel; δL_i is the noise equivalent temperature difference of the i-th channel; and $\delta(AOD)$ is the error of MODIS AOD products. According to the global-scale validation results of MODIS AOD products by Remer et al. [25], $\delta(AOD) = \pm 0.05 \pm 0.15 \times AOD$. The equivalent noise errors of MODIS are approximately 0.25 K for channels

29, 31, and 32, and about 0.05 K for channels 27, 28, and 33. The total model error obtained in this study under VZA=60° observation conditions is shown in Figure 5 [Figure 5: see original paper].

The results show that under VZA=60° observation conditions, $\Delta DSLR(AOD)$ caused by channel radiance L uncertainty increases with AOD, but $\delta(\Delta DSLR)$ decreases as AOD increases. Since the algorithm's inherent error accounts for a large proportion of the total error, $e(\Delta DSLR)$ shows a trend of first decreasing and then increasing with AOD, with the minimum value occurring at AOD=0.4. When AOD=0.4, $e(\Delta DSLR)$ is 9.6 $\mathrm{W \cdot m^{-2}}$. Under dust aerosol conditions, accurate AOD retrieval is crucial. Since errors from different input parameters may offset each other, the actual error may be smaller than the theoretically estimated value. Studies from other perspectives have reached similar conclusions, and $e(\Delta DSLR)$ increases with the observation zenith angle. When VZA=0°, the maximum root mean square error is 10.7 $\mathrm{W \cdot m^{-2}}$.

2.2 Validation Results Analysis

A total of 60 matched data points were finally selected from Huazhaizi Desert Station, Mixed Forest Station, Heihe Remote Sensing Station, and Zhangye Wetland Station. At Huazhaizi Desert Station, AOD ranges from 0.06 to 0.83 and WVC ranges from 0.12 to 2.84 $\mathrm{g \cdot cm^{-2}}$. At Mixed Forest Station, AOD ranges from 0.09 to 0.86 and WVC ranges from 0.44 to 3.43 $\mathrm{g \cdot cm^{-2}}$. At Heihe Remote Sensing Station, AOD ranges from 0.09 to 0.87 and WVC ranges from 0.29 to 3.09 $\mathrm{g \cdot cm^{-2}}$. At Zhangye Wetland Station, AOD ranges from 0.09 to 0.87 and WVC ranges from 0.33 to 3.02 $\mathrm{g \cdot cm^{-2}}$.

Figure 6 [Figure 6: see original paper] shows scatter plots of the inversion values from the two models against measured values during satellite overpass. At Huazhaizi Desert Station, where dust aerosol weather occurs mostly in spring, the DSLRA model achieves a root mean square error (RMSE) of 20.3 $\mathrm{W \cdot m^{-2}}$ and a bias of -5.8 $\mathrm{W \cdot m^{-2}}$, with an error range of -47.5 to 31.9 $\mathrm{W \cdot m^{-2}}$. At Mixed Forest Station, where dust aerosol weather occurs mostly in spring, the DSLRA model achieves an RMSE of 19.5 $\mathrm{W \cdot m^{-2}}$ and a bias of -7.8 $\mathrm{W \cdot m^{-2}}$, with an error range of -45.3 to 32.9 $\mathrm{W \cdot m^{-2}}$. At Heihe Remote Sensing Station, where dust aerosol weather occurs mostly in spring, the DSLRA model achieves an RMSE of 17.1 $\mathrm{W \cdot m^{-2}}$ and a bias of -1.8 $\mathrm{W \cdot m^{-2}}$, with an error range of -36.5 to 29.3 $\mathrm{W \cdot m^{-2}}$. At Zhangye Wetland Station, where dust aerosol weather occurs mostly in spring, the DSLRA model achieves an RMSE of 20.4 $\mathrm{W \cdot m^{-2}}$ and a bias of -12.3 $\mathrm{W \cdot m^{-2}}$, with an error range of -46.9 to 18.6 $\mathrm{W \cdot m^{-2}}$.

To better evaluate the application capabilities of the two models under dust aerosol conditions, scatter plots of model estimation errors against AOD and WVC are shown in Figure 7 [Figure 7: see original paper] and Figure 8 [Figure 8: see original paper], respectively. The results indicate that compared with DSLRC, the error distribution of DSLRA is more concentrated, with significant improvements in both RMSE and bias. The validation results using actual data for the DSLRA model show larger errors than those using simulated data, primarily because the model does not adequately account for necessary coefficient adjustments to TOA radiance values affected under dust aerosol conditions. Dust aerosol not only produces strong ALRF but also significantly affects TOA radiance, particularly for channels 29, 31, and 32, with maximum variation amplitudes reaching 3.51%. It can be concluded that the improved algorithm performs well under both light and heavy dust aerosol conditions. By accounting for and correcting errors caused by aerosol effects on TOA radiance, the model can also perform well in profiles with high water vapor content.

In addition to the above factors, AOD uncertainty must also be considered carefully. AOD has spatial heterogeneity and is influenced by topography, humidity, and temperature. In terms of vertical distribution, scattering and absorption vary at different levels, and variations in the vertical profile are important factors causing inaccuracies in many climate model predictions. Using lidar to detect the spatiotemporal distribution of atmospheric parameters and characterize aerosol properties is a viable method for improving model accuracy. However, these stations did not measure vertical profile data at corresponding times, which somewhat affects model validation and result analysis. Although OPAC provides optical properties of dust aerosol, these differ from the actual aerosol optical properties at the stations, such as differences in source regions, aerosol composition, particle size distribution, and their spatiotemporal variation patterns [26], which affect model validation results. Additionally, the misidentification of cloudy pixels as clear-sky pixels can substantially reduce TOA radiance, which is also a non-negligible issue in this study. The limited amount of station data meeting requirements may cause the accuracy of model field validation to be affected by individual sample points.

Overall, compared with DSLRC, DSLRA significantly improves the accuracy of DSLR estimation under dust aerosol conditions. However, limited by current research conditions and data, some aspects need improvement, particularly regarding the influence of aerosol vertical distribution profiles on DSLR retrieval.

3 Conclusions

(1) This algorithm is built upon AOD correction of partially sensitive channels and coefficient calibration, comprehensively considering factors such as AOD, WVC, and VZA. In vertical observation of simulated data, $e(\Delta DSLR)$ can be controlled within 9.6 $\mathrm{W \cdot m^{-2}}$. Sensitivity analysis results show that $e(\Delta DSLR)$ exhibits a trend of first decreasing and then increasing with AOD, with the minimum value occurring at AOD=0.4.

(2) In the validation at four stations in the Heihe River Basin, the improved DSLRA model achieves an RMSE of 17.1–20.4 $\mathrm{W \cdot m^{-2}}$ and a bias of –12.3 to –1.8 $\mathrm{W \cdot m^{-2}}$, basically meeting practical application requirements, though the overall error from site validation is larger than that from simulated data.

(3) Compared with DSLRC, DSLRA significantly improves the accuracy of DSLR estimation under dust aerosol conditions. However, limited by current research conditions and data, some aspects require improvement, particularly regarding the influence of aerosol vertical distribution profiles on DSLR retrieval. Future research will consider the impact of aerosol profile variations on DSLR, utilize lidar and sun photometer data for aerosol analysis, investigate aerosol vertical distribution profiles, and quantitatively analyze how profile-induced changes in aerosol extinction backscatter ratio and extinction coefficient affect DSLR retrieval. Additionally, we will increase site data to conduct universality studies on DSLR retrieval models under aerosol influence and carry out in-depth research on the effects of land cover type changes on DSLR retrieval accuracy.

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Note: Figure translations are in progress. See original paper for figures.