博 士 論 文 の 要 約

博士の専攻分野の名称：　博　士（農学）　　　　　　　　　　　　　氏名　　　鐘　国盛

Study on the impact of atmospheric pollution on eco-environment changes using satellite remote sensing technique
（衛星リモートセンシングを用いた生態環境変化への大気汚染の影響に関する研究）

Ground-level aerosols, also known as particulate matter (PM), are associated with human health and as such are regulated as a priority air quality pollutant. Recently, air pollution has become a matter of global concern as atmospheric aerosols play a very crucial role in air quality. Atmospheric aerosols have a significant influence on the radiative balance of the Earth and global climate change in both direct and indirect ways. On one hand, the atmospheric aerosols can directly reflect and absorb the incoming solar and terrestrial radiation. On the other hand, the atmospheric aerosols can affect the incoming radiation indirectly through modifying cloud formation and the microphysical properties of clouds. The study of atmospheric aerosol properties is therefore significant to understanding Earth system dynamics and atmospheric environment. Satellites are increasingly contributing to obtaining information on aerosol properties (e.g., the aerosol optical depth (AOD), the columnar concentration of particles, their sizes). In addition, the atmospheric aerosol is one of the largest uncertainties in surface observation from satellite-level, since aerosol distribution is often heterogeneous. Therefore, the remote sensing of the Earth’s surface results is affected by atmospheric gases and aerosol particles scattering and absorption.

The main objectives of this research are to develop an aerosol retrieval algorithm in aerosol properties retrieval from satellite observations, and to develop a self-correction approach to remove the atmospheric influence on vegetation indices.

The main contents of this thesis include 5 (Chapters 2-6) parts:

1. (Chapter 2) Cloud and Aerosol Imager (CAI), is one of the instruments on the Greenhouse gases Observing SATellite (GOSAT) for detecting and correcting cloud and aerosol interference. One important aerosol optical property, AOD, can reflect the characteristics of atmospheric turbidity and is the most frequently used monitoring parameter of atmospheric aerosols. A new algorithm for retrieving AOD over land from the CAI was developed. Determination of the surface reflectance has long been considered the primary task for estimating the optical properties of aerosols. The signal obtained by the space-borne sensor measures the radiance at the top of the Earth's atmosphere (TOA), which consists of two basic components: the radiance scattered by atmosphere and the radiance reflected by the surface. To derive the aerosol information, the surface contribution should be separated from the atmosphere contribution. Because the CAI shortwave infrared (SWIR) bands (1.6 μm) is less affected by atmospheric aerosols, the surface reflectance in the red band (0.67 μm) band can be estimated using a linear relationship between the surface reflectance at 0.67 μm and TOA reflectance at 1.6 μm. We used the co-located GOSAT and AErosol RObotic NETwork (AERONET) data from different regions over the globe to analyze their reflectance relationship. Our results confirmed that the relationships between the surface reflectance at 0.67 μm and TOA reflectance at 1.6 μm are not constant for different surface conditions. Under low AOD conditions (AOD at 0.55 μm < 0.1), a Normalized Difference Vegetation Index (NDVI) based regression function for estimating the surface reflectance of the 0.67 μm band from the 1.6 μm band was summarized, and it achieved good performance, proving that the reflectance relations of the 0.67 μm and 1.6 μm bands are typically

vegetation dependent. Since the NDVI itself is easily affected by aerosols, we combined the advantages of the Aerosol FRee vegetation Index (AFRI), which is aerosol resistant and highly correlated with regular NDVI, with our regression function, which can tune the various correlations of 0.67 μm and 1.6 μm bands for different surface types, and developed a new surface reflectance estimation algorithm. This algorithm was applied to AOD retrieval, and the validation results for our algorithm show that the retrieved AOD has a consistent relationship with AERONET measurements, with a correlation coefficient of 0.912, and approximately 67.7% of the retrieved data were within the expected error range ($\pm$ 0.1 $\pm$ 15% $AOD_{AERONET}$).

2. (Chapter 3) Variations introduced by atmospheric effects, absorption and scattering can considerably reduce the precision of the subsequent detections of the vegetation dynamics over the Earth's surface. I evaluated the performances of Atmospherically Resistant Vegetation Index (ARVI), Enhanced Vegetation Index (EVI), two-band-based EVI (EVI2), Visible Atmospherically Resistant Index (VARI) and AFRI for vegetation detection and monitoring with various AOD levels using the spatially and temporally matched Moderate Resolution Imaging Spectroradiometer (MODIS) and AERONET data. The TOA reflectance provided by the MODIS/Terra calibrated radiances (MOD02HKM) data were used to calculate the TOA vegetation indices (not atmospherically corrected), and the atmospherically corrected vegetation indices were calculated using the reflectance data from the MODIS surface reflectance product (MOD09HKM). The experimental results revealed that the TOA ARVI and TOA EVI are highly correlated with the atmospherically corrected NDVI for different levels of AODs. However, their TOA vegetation index values were somewhat different from the corresponding atmospherically corrected vegetation index values. AFRI outperformed other vegetation indices due to the smaller differences in their TOA and atmospherically corrected vegetation index values.

3. (Chapter 4) Vegetation indices calculated from satellite observations in the visible and infrared bands have been widely used for the assessment of vegetation cover and conditions. The NDVI is a commonly used vegetation index for the retrieval of the biophysical properties of the vegetation canopy. However, due to the significant disadvantages of NDVI, including that it is sensitive to atmospheric influences, there is a considerable reduction in the precision of the detection of vegetation dynamics at the satellite level. A self-correction method to minimize the atmospheric influences on vegetation indices was developed using MODIS data. Based on the linear relationship between the surface reflectance relationship in the 0.6 µm and 2.1 µm bands (2.1 µm band is less affected by atmospheric aerosols), the surface reflectance in the 0.6 µm band can be estimated. Under a median assumption in viewing geometry, we can derive a predicted AOD according to the TOA reflectance and estimated surface reflectance. The predicted AOD value can be considered as prior knowledge of the atmospheric conditions to actualize the self-correction procedure. Based on simulation results from a radiative transfer model, we summarized two empirical functions to correct the aerosol influences in near-infrared (NIR) and red bands. As a result, the corrected NIR and red bands can be directly used in the construction of vegetation indices (e.g., NDVI, SR); additionally, a single corrected band can be used to improve the accuracy of the SWIR-derived vegetation indices (e.g., AFRI). This method was applied in the construction of the corrected NIR-derived AFRI and the corrected NDVI, the performances of which were investigated under different aerosol loading conditions. The results revealed that under different AOD values, the atmospheric influences on the NIR and red bands were largely removed, and the corrected vegetation indices were generally closer to their theoretical values than the original vegetation indices.

4. (Chapter 5) A SWIR 2.1-µm-based self-correction method has been developed for the correction of the atmospheric influences in the red and NIR bands in Chapter 4. However, there are many sensors that only provide observations in the 1.6-µm SWIR band, and it is difficult to apply this correction method to the sensors without 2.1-µm bands. To overcome this issue, we analyzed the reflectance relationship between the 1.6 µm and 2.1 µm bands using the MODIS surface reflectance product, and attempted to adapt the 2.1-µm-based self-correction method to the 1.6-µm-based sensors, according to the reflectance relationship between the 1.6 µm and 2.1 µm bands. The results revealed that the reflectance relationship between the 1.6 µm and 2.1 µm bands is typically dependent on vegetation conditions. Based on the experimental results, an AFRI-based regression function

connecting the 1.6 μm and 2.1 μm bands was summarized. Under light aerosol loading (AOD at 0.55 μm < 0.1), the 2.1 μm reflectance derived by our method has an extremely high correlation with the true 2.1 μm reflectance (r-value = 0.928). Using the relationship between the 1.6 μm and 2.1 μm bands, the adaption of the correction method has been successfully accomplished. The performance of the 1.6-μm-based correction method has been tested with different levels of AOD by a comparison of the atmospherically corrected vegetation indices. The results showed that the atmospheric influences in the red and NIR bands were effectively corrected using the 1.6-μm-based correction method. The development of the 1.6-μm-based correction method offers the potential for 1.6-μm sensors to detect the vegetation dynamics in the presence of aerosols.

5. (Chapter 6) A Dark Target (DT) algorithm for GOSAT CAI in AOD retrieval over land was developed based on the strategy of MODIS DT algorithm. When retrieving AOD from satellite platforms, the determination of surface contributions is a major challenge. The MODIS DT algorithm is a mature and well-defined algorithm for estimating the surface reflectance and retrieving aerosol properties. In the MODIS DT algorithm (Collection 5 and Collection 6), surface reflectance at the 0.6 μm is estimated based on the relationship between the 0.6 μm and 2.1 μm bands. The relationship between the two bands is dependent on both geometry (scattering angle, an angle can be calculated using solar zenith/azimuth angle and satellite zenith/azimuth angle) and surface conditions ($NDVI_{SWIR}$, an aerosol resistant measure of vegetation 'greenness' using the 1.24-μm and 2.1-μm SWIR bands). However, the CAI only has the 1.6 μm band to cover SWIR wavelength. To resolve the difficulties in determining surface reflectance caused by the lack of 2.1-μm band data, the relationship between reflectance at 1.6 μm and at 2.1 μm summarized in Chapter 5 were used. Similar to the current MODIS DT algorithms, a CAI-applicable approach that uses AFRI and the scattering angle to account for the surface signal at 0.6μm was proposed based on the experimental results. It was then applied to the CAI sensor for AOD retrieval; the retrievals were validated by comparisons with ground-level measurements from AERONET sites. Validations show that retrievals from the CAI have high agreement with the AERONET measurements, with an r-value of 0.922, and 69.2% of the AOD retrieved data falling within the expected error envelope of ($\pm 0.1 \pm 15\% \, AOD_{AERONET}$).

This thesis introduced two new AOD retrieval algorithms for GOSAT TANSO-CAI sensor, and two self-correction methods to minimize the atmospheric influences in red and NIR bands based on MODIS data. In theory, these algorithms can be implemented for any satellite sensor that measure reflectance in corresponding wavelength. Expectedly, Greenhouse gases Observing SATellite 2 (GOSAT-2), the successor to GOSAT, will carry a new observation instrument: Cloud and Aerosol Imager 2 (CAI-2), and CAI-2 will have greatly improved observation capabilities over CAI. With regard to the second-generation sensor CAI-2, this work could be a meaningful reference, and the existing deficiencies caused by current instrument limitations can be expected to improve in the future.