Atmospheric Correction of Visible and Near-infrared Satellite Data using Radiance Components: an Improved Treatment of Adjacency Effect

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Abstract

An algorithm is presented for the atmospheric correction of satellite data in the visible and near-infrared spectral region. The algorithm consists of analytic equations which are described only with the radiance components easily obtained with a radiation transfer code such as MODTRAN3. A three-step approach is introduced to precisely evaluate the pixel reflectance. In the first step, the path radiance is removed and in the second and the third steps, the adjacency effect from the neighboring pixels is removed. Using this method, a sensitivity analysis is performed for the NOAA AVHRR channel 1 and channel 2. To obtain a test image, we consider the multiply scattered component and the indirectly ground-reflected component, both of which are dependent on an average reflectance around the target pixel. It is found that a precision of about 1% (channel 1) and 0.5% (channel 2) can be obtained with respect to the pixel reflectances if the same atmospheric conditions are applied both to the generation of the test image and to the retrieval of the reflectance image. The method is actually applied to AVHRR images with the optical thickness obtained from ground measurements synchronized with the satellite overpass. The present algorithm is suitable for cases in which the surface reflectance changes on a pixel by pixel basis. Since the algorithm is described with radiance components, its application to any type of satellite sensor is quite straightforward as compared with the conventional lookup table approach.

Keyword: satellite observation, NOAA AVHRR, atmospheric correction, adjacency effect, MODTRAN, radiance components

1. Introduction

In the visible and near-infrared spectral region, the purpose of the atmospheric correction of satellite image data is to derive the surface reflectivity for each pixel. This is accomplished by removing the atmospheric path radiance as well as the blurring due to the presence of neighboring pixels. In the visible and near-infrared bands, both this path radiance and adjacency effect are governed by the molecular and aerosol extinction processes in the atmosphere. Compared with the molecular extinction, the conditions of the aerosol extinction change quite significantly. If the column amount and the type of aerosol particles are specified, the extinction process in the atmosphere is effectively simulated by radiation transfer codes such as MODTRAN and 6S. Although MODTRAN is a very versatile code, its algorithm is based on an assumption that the ground surface has a uniform reflectivity. This limits its applicability to the calculation of the adjacency effect. On the contrary, the 6S code was developed for the purpose of atmospheric correction of satellite data. The adjacency effect is incorporated through the environmental function, \( F(r) \). Here \( r \) is the radius of a circular surface around the target. This function describes the probability that a photon, which would be directly transmitted to the target through the atmosphere, is in reality scattered and impacts the surface within a circle of radius \( r \) from the target. Since the reflectivity inside the circle is assumed to be uniform, this definition of \( F(r) \) implies that this scheme is practically applicable for very limited satellite images. For example, the blurring effect along the border between the land and sea surfaces cannot be handled properly.

The adjacency effect has been attracting attention in the field of satellite remote sensing from early days. Tanré et al. developed the framework of the environmental function which was incorporated in the 6S code later. In 1990, Richter proposed a fast atmospheric correction algorithm to be applied to Landsat TM images. As explained below, our
algorithm presented in this paper is based on his multi-step treatment. Recently, Takashima and Masuda considered the adjacency effect encountered in the coastal zone. The land and sea surfaces were simulated by checkerboard type of terrain composed of pixels, and a lookup table method was employed to implement the atmosphere-surface correction. Thome et al. applied this algorithm to the atmospheric correction of visible and near-infrared bands of the Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER) sensor.

In Richter's algorithm the atmospheric correction was conducted through a two-step calculation. In the present paper, we propose an extension of this algorithm. Compared with the original scheme by Richter, our description adopts simplified expressions for the target reflectance, namely only the radiance components are included in the analytical formula. We also introduce an additional third step, in which the reflectance of each pixel is re-calculated considering the radiance components from the neighboring pixels.

The effectiveness of this three-step algorithm is examined by means of a simulation, in which a test image is prepared by superposing the radiances from neighboring pixels on those directly reflected from the target pixel. Then, using the same atmospheric conditions, it is confirmed that the algorithm successfully reproduces the original reflectance image from the test image. In the calculation of the test image, more detailed distinction of radiance components is required than that usually done in the MODTRAN3 code. Thus, we additionally consider the multiply scattered component and the indirectly ground-reflected component which are dependent on an average reflectance around the target pixel.

In the present algorithm, any radiation transfer codes could be employed, since only the atmospheric and surface-reflected radiance components are needed for its implementation. Here we adopt the MODTRAN3.1 code for this purpose. Since the three-step algorithm is formulated using radiance components, it is thought to be more versatile than the lookup table approach, in which detailed tables have to be prepared for each sensor band in advance. When compared with the treatment using the environmental function such as in the 6S code, the present algorithm is suitable for cases in which the reflectance changes on a pixel by pixel basis.

For the purpose of sensitivity analysis and demonstration, we apply the method to satellite data received by NOAA-14 Advanced Very High-Resolution Radiometer (AVHRR) sensor. The images of channel 1 (visible, 0.57~0.71 µm) and channel 2 (infrared, 0.72~1.00 µm) are employed to prepare the test images, which are then subjected to the atmospheric correction.

2. MODTRAN3 code

The MODTRAN3 code employs the standard atmospheric models which include vertical profiles of aerosol extinction at 550 nm. The wavelength dependence of the extinction coefficient, absorption coefficient, and asymmetry parameter is also incorporated for several aerosol models, e.g. urban, rural, etc. In the code, Isaacs' two-stream algorithm and discrete-ordinate method (DISORT) are adopted as radiation transfer algorithms. Both of them calculate the radiance on a layer-by-layer basis. In the present paper, the calculation is conducted using the two-stream algorithm, which provides radiance values sufficiently accurate for the present purpose in a reasonable computation time. Under given atmospheric parameters and a surface reflectance, the code produces radiance values at the top of the atmosphere (TOA). The available components are the path radiance from single scattering (Lₚₛ), the path radiance from multiple scattering (Lₚₘₗ), the directly ground-reflected radiance (L₉₃), and the indirectly ground-reflected radiance (L₉ᵣ). Hereafter we use the notations of Lₚ=Lₚₛ+Lₚₘₗ, L₉=L₉₃+L₉ᵣ, and Lₚ₉₃=Lₚ+L₉. The properties of these components and the present elaboration will be explained in Secs. 4.1 and 4.2.

3. Two-step algorithm for atmospheric correction

3.1 Removal of path radiance

In Secs. 3.1 and 3.2, we briefly review the Richter's two-step algorithm. We consider the solar radiance (wavelength λ) that is reflected from a uniform Lambertian surface of reflectance ρ(λ). At the TOA, the radiative transfer calculation gives the radiance L(λ) in a form of

\[ L(λ) = L₀(λ) + \frac{E₉(λ)}{π} \rho(λ)[T₉₉(λ) + T₉₉₉(λ)] \]  

(1)

Here, T₉₉₉(λ) is the direct transmittance, T₉₉(λ) the diffuse transmittance, E₉(λ) the downward solar irradiance at the ground, and L₀(λ) the path radiance that would be observed for a uniform surface of ρ(λ)=0 (dark target). Similarly, the path radiance Lₚ(λ) is generally expressed as

\[ Lₚ(λ) = L₀(λ) + \frac{E₉(λ)}{π} \rho(λ) T₉₉₉(λ) \]  

(2)

As seen from this equation, Lₚ(λ)-L₀(λ) is assumed to be proportional to the surface reflectance. In a sensor bandwidth of λ₁~λ₂, Richter's treatment postulates that the model-derived planetary albedo, ρ,model, is given by
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\[ \rho_{\text{true}} = \frac{\pi d^2}{\cos \theta_0} \int \frac{L(\lambda) \Phi(\lambda) d\lambda}{E(\lambda) \Phi(\lambda) d\lambda} \]

\[ = a_0(\text{Atm}, \theta_0, \phi, \theta) + a_1(\text{Atm}, \theta_0, \phi, \theta) \times \rho \]  

where \( a_0 \) and \( a_1 \) are given by

\[ a_0 = \frac{\pi d^2}{\cos \theta_0} \int \frac{E(\lambda)(T_{\text{at}} + T_{\text{at}}) \Phi(\lambda) d\lambda}{2 \int E(\lambda) \Phi(\lambda) d\lambda} \]  

and

\[ a_1 = \frac{d^2}{\cos \theta_0} \int \frac{E(\lambda)[T_{\text{at}} + T_{\text{at}}] \Phi(\lambda) d\lambda}{E(\lambda) \Phi(\lambda) d\lambda} \]  

Here, \( \text{Atm} \) refers to atmospheric parameters, \( \theta_0 \) the solar zenith angle, \( \phi \) the relative azimuth angle between the sun-target and target-sensor directions, \( \rho \) the ground reflectance expressed as \( \rho = \frac{\pi d^2}{\cos \theta_0} E(\lambda) \Phi(\lambda) d\lambda \), \( d \) the astronomical distance between the sun and the earth, \( \Phi(\lambda) \) the sensor response function, and \( E(\lambda) \) the solar irradiance at the TOA. In Eqs. (4) and (5), \( a_0 \) represents the reflectance that is arising from the atmosphere (corresponding to the path radiance), and \( a_1 \) denotes the TOA reflectance for \( \rho = 1 \). These coefficients are dependent on the atmospheric conditions as well as on the geometric conditions under which a satellite observation is made. It is assumed that the planetary albedo, \( \rho_{\text{measured}} \), which is actually measured by a satellite sensor, is equal to \( \rho_{\text{true}} \) in Eq. (3). Then by replacing the surface reflectance \( \rho \) with \( \rho_{\text{true}} \) and solving this equation with respect to \( \rho_{\text{true}} \), the following equation is obtained as a first-step atmospheric correction:

\[ \rho_{\text{true}} = a_1 \left[ \rho_{\text{measured}} - a_0 \right] \]  

Thus, it is apparent that this step removes the atmospheric contribution from a satellite image.

### 3.2 Correction of the adjacency effect

For a uniform surface, the TOA radiance is given by Eq. (1). For a non-uniform surface, on the other hand, the Richter’s algorithm deals with the adjacency effect in the following manner. We consider a target pixel of reflectance \( \rho \) within a region of an average reflectance of \( \bar{\rho} \). Then, the TOA radiance \( L(\lambda) \) which a satellite sensor observes for the target pixel is given by

\[ L(\lambda) = L_{\text{at}}(\lambda) + \frac{E(\lambda)}{\pi} [\rho(\lambda)T_{\text{at}}(\lambda) + \bar{\rho}(\lambda)]T_{\text{at}}(\lambda) \]  

By comparing this equation with Eq. (1), one obtains

\[ \rho_{\text{adj}}(T_{\text{at}} + T_{\text{at}}) = \rho T_{\text{at}} + \bar{\rho} T_{\text{at}} \]  

Here we have omitted \( \lambda \) for simplicity. Further, it is assumed that \( \bar{\rho} \) is equal to the average reflectance of \( N \times N \) pixels centered at the target, i.e.,

\[ \bar{\rho} = \rho_{\text{true}}^1 \]

\[ = \frac{1}{N^2} \sum_{j=1}^{N^2} \rho_{\text{mod}}^i \]  

Here we call \( N \) the range parameter. In Eq. (8), we regard the reflectance \( \rho \) on the right-hand side as \( \rho_{\text{adj}}^2 \), a second-step value in the atmospheric correction. Thus, we obtain

\[ \rho_{\text{adj}}^2 = \rho_{\text{adj}}^1 + q(\rho_{\text{adj}}^1 - \rho_{\text{true}}^1) \]  

Here, the parameter \( q \) is defined as

\[ q = \int T_{\text{at}}(\lambda) \Phi(\lambda) d\lambda \]  

This parameter describes the ratio between the diffuse transmittance and the direct transmittance, representing the relative importance of the adjacency effect.

### 4. Three-step algorithm for atmospheric correction

#### 4.1 Improvement of the two-step algorithm

In the calculation of Eqs. (1)–(11), a number of parameters have to be evaluated, such as the direct and diffusive transmittance, \( T_{\text{at}}(\lambda) \) and \( T_{\text{at}}(\lambda) \), solar spectrum \( E(\lambda) \), downward solar irradiance at the ground level \( E_{\text{at}}(\lambda) \), etc. This situation can be simplified by rewriting these formula with the radiance components which are readily obtained from a radiation transfer code. If we assume in Eqs. (3)–(5) that the response function \( \Phi(\lambda) \) takes a constant value within the sensor bandwidth, the equation of the first-order reflectance, \( \rho_{\text{true}}^1 \), can be simplified as follows (see Appendix A):

\[ \rho_{\text{true}}^1 = \rho_{\text{true}} \]  

\[ = \rho_{\text{true}} \]  

\[ = \frac{L_{\text{at}} - L_{\text{total}}}{L_{\text{total}} - L_{\text{at}}} \]  

Here, \( \rho_{\text{true}} \) is the surface reflectance used in the MODTRAN calculation, \( L_{\text{at}} \) is the pixel radiance observed by the sensor, and \( L_{\text{total}} \) and \( L_{\text{at}} \), respectively, are the total and path radiances at the TOA obtained from the MODTRAN calculation. Figure 1(a) shows the dependence of MODTRAN radiance components on the surface reflectance. This is a result calculated for the AVHRR channel 1 using an aerosol optical thickness of 0.198 at 550 nm, corresponding to a data over Chiba at 13:51 JST on December 5, 1997. As can be seen from this figure, the value of \( L_{\text{total}} - L_{\text{at}} \) is proportional to the surface reflectance to a good approximation. This indicates that in Eq. (12) the ratio of \( \rho_{\text{true}} \) (\( L_{\text{total}} - L_{\text{at}} \)) does not depend on the value of \( \rho_{\text{true}} \) assumed in the MODTRAN calculation.
in the present simulation, we use $\rho_{\text{MOD}} = 0.2$.

As also explained in Appendix Eq. (A13), the second-order expression of the adjacency effect correction becomes

$$\rho^{(2)} = \rho^{(1)} + \frac{L_e - L_0}{L_b} (\rho^{(1)} - \tilde{\rho}^{(1)}) \quad (13)$$

where $L_e$ is the TOA radiance due to the ground reflection and $L_p$ is the path radiance; these are also obtainable through the usual MODTRAN calculation, as given in Fig. 1 (a).

Now, we consider improvement of the correction of the adjacency effect. On the right-hand side of Eq. (8) we have a term that includes $\rho^{(1)}$. Since $\rho^{(1)}$ is obtained from $\rho^{(3)}$, the pixel reflectance before the adjacency-effect correction, the corrected reflectance $\rho^{(2)}$ is still affected by the adjacency effect. In order to consider this effect, here we use the following expression, similar to Eq. (8), to define $\rho^{(2)}$:

$$\rho^{(2)} = \rho^{(1)} + q (\tilde{\rho}^{(1)} - \tilde{\rho}^{(2)}) \quad (14)$$

Hence, we have

$$\rho^{(3)} = \rho^{(2)} + q (\tilde{\rho}^{(3)} - \tilde{\rho}^{(2)}) \quad (15)$$

Repeated application of similar procedure leads to an expression for $k$-th order correction of the adjacency effect:

$$\rho^{(k)} = \rho^{(k-1)} + \frac{L_e - L_0}{L_b} (\rho^{(k-1)} - \tilde{\rho}^{(k-1)}) \quad (16)$$

for $k = 3, 4, \ldots$

Tests have shown that usually the progression of $\rho^{(k)}$ converges for $k \geq 3$, and $k = 3$ gives sufficient accuracy. Here we use $\rho^{(3)}$ as the final form of the atmospheric correction. Thus, we have derived a three-step algorithm based on Eqs. (12), (13), and (15).

With respect to the present algorithm of the atmospheric correction, the simplified form of the expressions are obtained at the expense of consideration on the exact spectral response of the satellite sensor. This treatment is justified since inclusion of the sensor response function becomes meaningful only when the information on the wavelength dependence of target reflectance is available at the same time. Unfortunately, this is hardly the case in the usual procedure of the atmospheric correction of satellite remote-sensing data.

4.2 Validation method of the three-step algorithm

In this subsection, we describe the method of simulation used for the validation of the present three-step algorithm. For the implementation of this simulation, first it is necessary to calculate the TOA radiances (or equivalently, the planetary albedo) which would be observed by a satellite sensor under given atmospheric and surface conditions. Obviously, in addition to the contribution from the target pixel itself, the radiances should include those from the adjacent pixels. The conventional calculation using the MODTRAN code becomes insufficient in this respect, since the code basically assumes a ground surface which exhibits uniform reflectivity. Instead, here we rearrange the MODTRAN source code so that we can separately calculate the ground-reflected and path radiance components that are influenced by the scattering process at adjacent pixels around the target.

As mentioned previously, the MODTRAN code gives the TOA total radiance in a form of

$$L_{\text{total}} = L_{\text{g}} + L_{\text{p}} + L_{\text{pm}} \quad (17)$$

where $L_{\text{g}}$ is the directly ground-reflected radiance, $L_{\text{p}}$ the indirectly ground-reflected radiance, $L_{\text{pm}}$ the path radiance due to single scattering, and $L_{\text{pm}}$ the path radiance due to multiple scattering. A detailed analysis shows that among these components, $L_{\text{pm}}$ includes a component that is proportional to the
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Fig. 2 Schematic illustration of the six radiance components.

Fig. 3 Flow chart of the sensitivity analysis of the present three-step atmospheric correction algorithm.

Table 1 NOAA AVHRR data over Chiba and related parameters. $\tau_{550}$ is the aerosol optical thickness at 550 nm derived from the simultaneous observation using a sunphotometer. $S_i$ and $I_i$ are the calibration (slope and intercept) constants used in eq. (22) for the channel $i$ ($i=1, 2$) NOAA data.
adjacency effect. In the calculation of \( \bar{\rho} \), we employ \( N_{\text{sim}} \times N_{\text{sim}} \) pixels around the target pixel as in the case of Eq. (9). Then, the \( L_{\text{pix}} \) image is subjected to the atmospheric correction procedure through Eqs. (12)-(15). For this atmospheric correction, we use a range parameter \( N = N_{\text{ac}} \) which may be the same as or different from \( N_{\text{sim}} \). The result is evaluated for the second- and third-step reflectances, \( \bar{\rho}^{(j)} \) \( (j=2, 3) \), by means of relative errors defined as \( r^{(j)} = (\bar{\rho}^{(j)} - \rho_{t}) / \rho_{t} \).

Since for each pixel, the relative importance of the adjacency effect differs in accordance with the pixel reflectance, we make a statistical consideration for each pixel group that consists of pixels characterized by the same reflectance. We define the average value of the relative error \( r^{(j)} \) as

\[
\bar{r}^{(j)}(\rho_{t}) = \frac{1}{m(\rho_{t})} \sum_{i=1}^{m(\rho_{t})} \frac{r^{(j)}_{i}}{m(\rho_{t})}
\]

(20)

where the summation is carried out for \( m(\rho_{t}) \) pixels which have the original reflectance of \( \rho_{t} \). Similarly, we define the standard deviation of \( r^{(j)} \) as

\[
\sigma^{(j)}(\rho_{t}) = \left[ \frac{1}{m(\rho_{t})-1} \sum_{i=1}^{m(\rho_{t})} (r^{(j)}_{i} - \bar{r}^{(j)}(\rho_{t}))^{2} \right]^{1/2}
\]

(21)

If the atmospheric correction of the \( L_{\text{pix}} \) image were carried out in a perfect way, both \( \bar{r}^{(j)}(\rho_{t}) \) and \( \sigma^{(j)}(\rho_{t}) \) become zero.

5. Sensitivity analysis using the AVHRR data

5.1 AVHRR data

Table 1 shows the NOAA 14 AVHRR data used in the present simulation and analysis. The satellite overflight took place between 1:30 and 3:00 p.m. over the Chiba area: each image \((190 \times 190 \) pixels) was taken at the near nadir angle centered at the area. Both channel 1 and channel 2 images are employed here. In the images No.1 (December 5, 1997) and No. 2 (December 28, 1998) of the table, the scenes are mostly cloud free, though limited part of the sea surface is eclipsed. In the image No. 3 (April 14, 1999), half of the land surface (north part of the Kanto plane) is covered by clouds. In No. 4 (July 29, 1999), scattered distribution of clouds is found above the land area.

The AVHRR data, originally in a form of 10 bit digital data, can be converted to the reflectivity. According to the NOAA USERS GUIDE(15), this is accomplished by means of the following formula:

\[
\rho_{\text{measured},i} = S_{i} \times \text{DN}_{i} + I_{i}
\]

(22)

Here the subscript \( i (=1,2) \) refers to the channel number, and \( S_{i} \) and \( I_{i} \) respectively, are the slope and intercept coefficients: the most updated values of these are obtainable from National Environmental Satellite Data and Information Service (NESDIS)(3). The coefficients relevant to each data are listed from the fifth through eighth columns of Table 1. If we compare the absolute values of \( S_{i} \) and \( I_{i} \), between the data No. 1 and No. 2, for instance, they are both larger for the former; this results in differences in the resolution of reflectivity, \( \Delta_{\rho} \), which becomes 0.0034 in channel 1 and 0.0159 for channel 2.

The radiance for each channel is obtained from the reflectivity as

\[
L_{\text{pix}} \bar{\rho} + \frac{F_{i}}{100\pi}
\]

(23)

Here, \( F_{i} \) is a constant which describes the solar irradiance integrated over the sensor bandwidth with proper weighting based on the sensor response function. For NOAA 14, we have \( F_{1} = 221.42 \text{ W/m}^2 \) and \( F_{2} = 252.29 \text{ W/m}^2 \).

For each satellite data in Table 1, we use the aerosol optical thickness obtained using a sunphotometer at the time of the NOAA 14 overflight. The value at 550 nm, \( \tau_{550} \), which is required as an input parameter in the MODTRAN calculation, is determined by the interpolation of the eight-wavelength sunphotometer data. The values are listed in the fourth column of the table. The value of \( \tau_{550} \) is relatively large for the data No. 2 and No. 3.

For the other parameters given to the MODTRAN code, we employ the standard atmosphere (midlatitude) and the urban aerosol model for the wavelength dependence of the aerosol extinction. The wavenumber region is 14,184 - 17,467 cm\(^{-1}\) for channel 1 and 9,975 - 13,840 cm\(^{-1}\) for channel 2. Both the bin width and the width of the triangular function are taken to be 40 cm\(^{-1}\). This corresponds to the assumption of the uniform sensitivity over the sensor bandwidth (as mentioned in Sec. 4.1) in the calculation of the radiance components.

5.2 Images for simulation

For the implementation of the method described in Sec. 4.2, we prepare two types of images. The first one is the "white noise" image (Fig. 4), composed of pixels which have random

![Fig. 4](image-url)
reflectivity in a range of $\rho_t=0.002\sim0.5$. Since the step of reflectivity is 0.002 and the image size is 400×400 pixels, there exist 500~700 pixels that have the same value of the reflectivity. Using these sets of pixels, we apply the statistical approach to evaluate the correction of the adjacency effect, as explained in Sec. 4.2. In the construction of the $L_{pix}$ image, we calculate the average reflectance $\bar{\rho}$ assuming $N_{sim}=3$ and 15.

The other type is the images around the Chiba area based on the real satellite data after the atmospheric correction. In

![Fig. 5 Retrieval errors for the noise image. Error values in terms of the average $\bar{\rho}(\rho_t)$ in Eq. (20) and the standard deviation $\sigma(\rho_t)$ in Eq. (21) are plotted against $\rho_t$. The average reflectance is calculated for (a) 3 × 3, and (b) 15×15 pixels.]

![Fig. 6 Retrieval errors for the Chiba images. (a) (AVHRR channel 1) and (b) (channel 2) are for the image No. 2 (December 28, 1998), and (c) (channel 1) and (d) (channel 2) are for the image No. 3 (April 14, 1999). Pixel reflectances are retrieved with an accuracy of about 1% (channel 1) and 0.5% (channel 2) for pixels with relatively low reflectance of less than 0.2.]

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the images, highly reflective pixels are present for both the land and sea areas due to clouds. The pixels with \( \rho_l > 0.5 \) are regarded as having \( \rho_l = 0.5 \). The size of the Chiba images is 186 \( \times \) 186. With the step of reflectivity between 0.009 to 0.011, we have about 10 to 3,000 pixels that are with the same value of the reflectivity. Among the four AVHRR images mentioned above, we choose images No. 2 and No. 3 with relatively large values of the optical thickness to construct the test images. In the MODTRAN calculation using eq. (19), we use the optical thickness at 550 nm (\( \tau_{550} \)) in Table 1. For the calculation of the average reflectance \( \bar{\rho} \), we study two cases of \( N_{\text{sim}} = 3 \) and \( N_{\text{sim}} = 15 \). It is noted that in the practical application of atmospheric correction, the choice of the range parameter \( N \) is crucial for the exact removal of the adjacency effect (see also Sec. 6.2 below). In the present simulation, the essential aspect is not to determine the range parameter for each image, but to investigate how the accuracy in the retrieval of the surface reflectance is influenced by the range parameter \( N = N_{\text{ac}} \) defined in eq. (9).

5.3 Retrieval with the same range parameter

First we consider the case in which the same value of the range parameter is used for the preparation of the test image (\( N_{\text{sim}} \)) and for the atmospheric correction (\( N_{\text{ac}} \)). The method of Sec. 4.2 is applied to the noise image and Chiba images.

The result for the noise image is depicted in Fig. 5: (a) is for \( N = 3 \) and (b) is for \( N = 15 \). Here \( N = N_{\text{ac}} = N_{\text{sim}} \). In these figures, the average \( \bar{\rho}(\rho_l) \) and the standard deviation \( \sigma^{(2)}(\rho_l) \), defined in Eqs. (20) and (21), are plotted against \( \rho_l \). For both \( N = 3 \) and \( N = 15 \), the difference between \( \bar{\rho}^{(2)}(\rho_l) \) (after the second-step atmospheric correction) and \( \bar{\rho}^{(3)}(\rho_l) \) (after the third-step correction) is small. On the other hand, improvement in \( \sigma^{(2)}(\rho_l) \) is evident, especially for the pixels with reflectivity smaller than \( \sim 0.1 \). Comparing Fig. 5 (a) and (b), it is seen that increase in the range parameter yields more smoothed curves both for the average and the standard deviation. At the same time, for \( N = 15 \), both \( \sigma^{(2)}(\rho_l) \) and \( \sigma^{(3)}(\rho_l) \) become smaller, and the variation range of \( \bar{\rho}^{(2)}(\rho_l) \) becomes more limited. This indicates that better accuracy is obtained if the relevant region contains more pixels.

The results for the Chiba images are shown in Fig. 6: (a) is for the AVHRR channel 1 and (b) is for channel 2 of the image No. 2 (December 28, 1998) and (c) channel 1 and (d) channel 2 of the image No. 3 (April 14, 1999). The step of the reflectivity, \( \Delta \rho_l \), is about 0.01. Compared to Fig. 5 calculated for the noise image, the dependence on the reflectivity \( \rho_l \) becomes less smooth. This is ascribed to the smaller number of pixels at each reflectivity bin. Nevertheless, improvement in the third-step result is evident as compared with the second-step one. For the pixel reflectance of less than \( \sim 0.2 \), the retrieved pixel reflectance has an accuracy better than 1% for channel 1 and 0.5% for channel 2. In the case of the image No. 3, the relative error increases with \( \rho_l \). This is ascribed to the cloud pixels which are relatively small in number (less than 20 pixel for each reflectivity) yet quite influential to the neighboring pixels.

5.4 Retrieval with different range parameters

In this section, we consider the case in which different range parameters are used for the preparation of the test image and for the atmospheric correction. This consideration is useful to evaluate how the range affects the results in the present algorithm of the atmospheric correction. We use \( N_{\text{sim}} \) for \( N \) in the construction of the \( L_{\text{pix}} \) image (the noise image or the Chiba image, as mentioned in Sec. 5.2), and \( N_{\text{ac}} \) in the subsequent atmospheric correction. In the following simulation, \( N_{\text{ac}} \) is changed as \( N_{\text{ac}} = 3, 5, 7, 9, 11, 13, \) and \( 15 \) for each of \( N_{\text{sim}} = 3 \) and 15. The results are shown in Fig. 7: (a) is for AVHRR channel 1 with \( N_{\text{sim}} = 3 \), (b) for channel 2 with \( N_{\text{sim}} = 3 \), (c) for channel 1 with \( N_{\text{sim}} = 15 \), and (d) for channel 2 with \( N_{\text{sim}} = 15 \). In these figures, the average and standard deviation of the relative error are plotted against \( N_{\text{ac}} \) for the result after the third-step atmospheric correction applied to a pixel group of \( \rho_l = 0.05 \).

Fig. 7 Dependence of the retrieval errors on the range parameter for the atmospheric correction. (a) (AVHRR channel 1) and (b) (channel 2) are obtained with \( N_{\text{sim}} = 3 \), and (c) (channel 1) and (d) (channel 2) are with \( N_{\text{sim}} = 15 \). The average and standard deviation of the relative error are plotted against \( N_{\text{ac}} \) for the result after the third-step atmospheric correction applied to a pixel group of \( \rho_l = 0.05 \).
deviation of the relative error are plotted against \(N_{\text{ac}}\) for the result after the third-step atmospheric correction for a pixel group of \(\rho_0 = 0.05\). Figure 7 clearly indicates that as the difference \(|N_{\text{ac}} - N_{\text{em}}|\) increases, both the average \(\bar{\rho}^{(3)}(\rho_0)\) and the standard deviation \(\sigma^{(3)}(\rho_0)\) increase. For \(N_{\text{em}} = 3\), both values tend to saturate as \(N_{\text{ac}}\) is increased. The largest deviation, found for the case of \(N_{\text{em}} = 3\) and \(N_{\text{ac}} = 15\), is about \(-0.25\) (\(\rho^{(3)}\) is by 25% smaller than \(\rho_0\)) for channel 1, and \(-0.2\) for channel 2. For \(N_{\text{em}} = 15\), on the other hand, both the average and standard deviation of the relative error significantly increase as \(N_{\text{ac}}\) decreases. An average error of nearly 100% is observed for \(N_{\text{ac}} \sim 7\). This simulation clearly shows that in order to obtain good accuracy in the correction of the adjacency effect, it is desirable to choose \(N_{\text{ac}}\) that is equal to or slightly larger than \(N_{\text{em}}\).

6. Atmospheric correction of AVHRR images

6.1 Relation between \(L_{\text{pix}}\) and \(L_{\text{gd}}\)

Now we apply the present algorithm to the actual AVHRR images given in Table 1. First we make an overview concerning the relation between \(L_{\text{pix}}\) and \(L_{\text{gd}}\) for channels 1 and 2, since \(L_{\text{gd}}\) is the most important component deduced from satellite images. In Fig. 8 we show the result for the data No. 1 (13:51 JST on December 5, 1997). Here we neglect the adjacency effect, since this obscures the intrinsic relationship between the input \((L_{\text{pix}})\) and output \((L_{\text{gd}})\) radiances. For channel 1, it is seen from the figure that the value of \(L_{\text{gd}}\) is approximately half as large as that of \(L_{\text{pix}}\). This is due to the fact that in the visible region of the spectrum, large contribution comes from the path radiance arising from the atmospheric scattering. In the case of channel 2, on the other hand, its effect becomes less prominent, and the role of the ground-reflected component becomes more important. Hence, starting from the same value of \(L_{\text{pix}}\), we obtain a value of \(L_{\text{gd}}\) for channel 2 larger than that for channel 1.

6.2 Second- and third-step corrections

Here we study how the correction of the adjacency effect manifests itself in actual AVHRR images. For that purpose, we tentatively assume a range parameter of \(N = 15\), corresponding to a surface area of 16.5\(\times\)16.5 km\(^2\). In general, the optimum value of the range parameter \(N\) depends on various conditions of the atmosphere and ground surface\(^{11, 12}\). When the aerosol optical thickness is relatively small, the increased contribution from molecular scattering tends to enlarge the value of \(N\). Its value is also critically dependent on the difference in the reflectivity of the target and neighboring pixels. It is expected that the aerosol vertical distribution plays a significant role as well. All these considerations are beyond the scope of this paper: further work is needed in this respect\(^{17}\).

Figure 9 shows the reflectance image of channel 2 after the third-step correction (data No. 2, 14:22 JST on December 28, 1998). The pixel reflectance is depicted in a range of 0 to 0.4: the value exceeding 0.4 is also included in the area of 0.4. The area with high reflectivity on the right middle and below are due to clouds. In the image before correction (the image of \(D(\text{measured})\), i.e., the apparent reflectivity at the TOA) the reflectivity is distributed in a relatively narrow range of 0 to 0.05. After the atmospheric correction, the distinction becomes much emphasized, with the reflectance of 0.15 to 0.4 for the land surface and below 0.03 for the sea surface. For channel 1, we observe a similar tendency: before correction, the reflectivity is distributed in a range of 0.0 to 0.05, while

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Fig. 8 Relation between \(L_{\text{pix}}\) and \(L_{\text{gd}}\) calculated for AVHRR channels 1 and 2 (13:51 JST on December 5, 1997).

Fig. 9 Reflectance image of AVHRR channel 2 (14:22 JST on December 28, 1998) after the third-step atmospheric correction.
after the atmospheric correction, the distribution exhibits two peaks around 0.03 and 0.07, corresponding to the sea and land surfaces, respectively.

Figure 10 illustrates the results of the adjacency-effect correction for AVHRR channels 1 and 2 (14:22 JST on December 28, 1998). (a) $\rho^{(1)} - \rho^{(3)}$ for channel 1, (b) $\rho^{(2)} - \rho^{(3)}$ for channel 1, (c) $\rho^{(1)} - \rho^{(3)}$ for channel 2, and (b) $\rho^{(2)} - \rho^{(3)}$ for channel 2.

6.3 Seasonal variations

As illustrated in Fig. 11, two regions are arbitrarily chosen, as representing urban and vegetation areas. The values of normalized vegetation index

$$NDVI = \frac{\rho^{(3)}_2 - \rho^{(3)}_1}{\rho^{(3)}_1 + \rho^{(3)}_2}$$

are calculated for each of them to study seasonal variations. Here the subscript stands for the AVHRR channel number. The urban area is located around the Chiba city, while the vegetation area is at the center of the Boso peninsula, where vegetation coverage (mainly forest) persists throughout the year. Both in the urban and vegetation areas, NDVI tends to increase as a result of the atmospheric correction. For each season, the increase is from 0.05 to 0.1 for the urban area and from 0.1 to 0.2 for the vegetation area. Thus, the increase is larger for the latter type of the surface. The seasonal variation is relatively small in the vegetation area, whereas in the urban area, NDVI is larger by about 0.1 in summer than in winter, reflecting the change in vegetation coverage.

7. Conclusions

We have described an algorithm for the atmospheric correction of satellite data. Our three-step algorithm has the characteristics that the path radiance and the adjacency effect are corrected on the basis of analytic equations which involve only the radiance components. The radiance components are readily obtained using a radiation transfer code such as the
MODTRAN3 code. By using the optical thickness observed with a sunphotometer, we have implemented the atmospheric correction of NOAA AVHRR data for several scenes over the Kanto area. Sensitivity analysis has shown that if proper atmospheric conditions are provided, the present algorithm is capable of retrieving the pixel reflectances with an accuracy of about 1% (channel 1) and 0.5% (channel 2) for areas with relatively low reflectance of less than 0.2. We believe that our method is more suitable for practical applications than the conventional methods, most of which is based on the lookup table approach that requires detailed calculation in advance. Further extension of the present method will include the determination of the reflectivity only from the satellite data by using e.g. the dark target method. Another important issue is the consideration on the magnitude of the range parameter N. This is closely related to the evaluation of the influence of the aerosol vertical profile on the adjacency effect. Both of these extensions are under progress.

References

15) http ://www2.ncdc.noaa.gov/docs/intro.htm

Appendix A

We assume that the sensor response function is constant (\( \Phi(\lambda) = 1 \)) in the bandwidth. Then, the total radiance at the TOA obtained from the radiation transfer calculation becomes

\[
L_{\text{total}} = \int_{\lambda_1}^{\lambda_2} L(\lambda) \Phi(\lambda) d\lambda = L_0 + \frac{E^s}{\pi} \rho_{\text{MOD}}[T_{\text{dir}} + T_{\text{diff}}]
\]

where

\[
L_0 = \int_{\lambda_1}^{\lambda_2} L_0(\lambda) \Phi(\lambda) d\lambda
\]

\[
\frac{E^s}{\pi} \rho_{\text{MOD}} T_{\text{dir}} = \int_{\lambda_1}^{\lambda_2} \frac{E_s(\lambda)}{\pi} \rho(\lambda) T_{\text{dir}}(\lambda) \Phi(\lambda) d\lambda
\]

\[
\frac{E^s}{\pi} \rho_{\text{MOD}} T_{\text{diff}} = \int_{\lambda_1}^{\lambda_2} \frac{E_s(\lambda)}{\pi} \rho(\lambda) T_{\text{diff}}(\lambda) \Phi(\lambda) d\lambda
\]

(1)
Similarly, for the path radiance we obtain
\[ L_p = \int \frac{1}{\lambda_1} L_\phi(\lambda) \Phi(\lambda) d\lambda \]
\[ = L_0 + \frac{E_\phi}{\pi} \rho_{\text{MOD}} T_{\text{dif}} \]
(A5)
By solving this equation with respect to the diffuse transmittance \( T_{\text{dif}} \), we have
\[ T_{\text{dif}} = \frac{\pi E_\phi \rho_{\text{MOD}}}{\lambda_0} (L_p - L_0) \]
and putting this into Eq. (A1), the direct transmittance is obtained to be
\[ T_{\text{dir}} = \frac{\pi E_\phi \rho_{\text{MOD}}}{\lambda_0} (L_{\text{total}} - L_p) \]
(A7)
The ground reflection component is given by \( L_g = L_{\text{total}} - L_p \). Inserting these expressions into Eqs. (4) and (5), \( a_0 \) and \( a_1 \) are calculated to be
\[ a_0 = \frac{\pi d^2}{E_\phi \cos \theta_\phi} L_0 \]
(A8)
\[ a_1 = \frac{\pi d^2}{E_\phi \cos \theta_\phi} \frac{L_{\text{total}} - L_p}{\rho_{\text{MOD}}} \]
(A9)
Here the solar irradiance \( E_s \) is given by
\[ E_s = \int \frac{1}{\lambda_1} E_\phi(\lambda) \Phi(\lambda) d\lambda \]
(A10)
By substituting Eqs. (A8) and (A9) into Eq. (6), the expression for the first-step correction becomes
\[ \rho^{(1)} = \frac{\rho_{\text{MOD}}}{L_{\text{total}} - L_0} \left( \frac{E_\phi \cos \theta_\phi}{\pi d^2} \rho_{\text{measured}} - L_0 \right) \]
\[ = \rho_{\text{MOD}} \frac{L_{\text{pix}} - L_0}{L_{\text{total}} - L_0} \]
(A11)
where the pixel radiance is defined as
\[ L_{\text{pix}} = \frac{E_\phi \cos \theta_\phi}{\pi d^2} \rho_{\text{measured}} \]
(A12)
Similarly, for the coefficient \( q \) that appears in the second- and third-step corrections, we obtain
\[ q = \int \frac{1}{\lambda_1} T_{\text{dif}}(\lambda) \Phi(\lambda) d\lambda \]
\[ = \frac{T_{\text{dif}}}{T_{\text{dir}}} \]
\[ = \frac{L_p - L_0}{L_i} \]
(A13)
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