Retrieval of aerosol optical properties over Chiba land area from Landsat/TM imagery

Part I: Determination of spatial distribution of aerosol optical thickness

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Abstract:

Satellite remote sensing data provide information on two-dimensional distributions of both the surface albedo and optical thickness of the atmosphere. In this work, we report the method of separating the contributions of the surface albedo and aerosol optical thickness from Landsat-5 TM visible-band data taken over the Chiba urban area. We focus on the determination of surface albedo from the data observed on a relatively clear day. It is shown that when the aerosol optical thickness is small, the atmospheric correction is not greatly affected by the aerosol model employed. The resulting surface albedo distribution from the clear day, in turn, is used to determine the aerosol distribution from the turbid image in the same season.

keywords: Landsat TM, Atmospheric correction, Albedo, Aerosol model

1. Introduction

In the analysis of satellite remote sensing data, the atmospheric correction technique is useful to derive the accurate distribution of surface albedo values that are free from the “contamination” due to the atmospheric radiances [1-3]. From the viewpoint of the atmospheric studies, the precise knowledge of the surface albedo leads to the possibility of deriving the aerosol distribution from the satellite data. Over the ocean surfaces, the method has been applied to derive aerosol distributions [1]. Over the land surfaces, however, the application of this technique has been rather limited [2] because of the high variability of the surface albedo, in addition to the spatial variability in the aerosol properties.

In the present paper, we demonstrate that the separation of the surface and atmospheric (aerosol) contributions can be achieved by suitably choosing satellite datasets within a season. The test area is the Chiba area, inside the Tokyo metropolitan area along the east coast of the Tokyo Bay. The visible band images of Landsat-5/Thematic Mapper (TM) are analyzed by means of a fast atmospheric correction algorithm reported by Minomura et al. [3].

2. Theory

2-1. Relationship between surface albedo and optical thickness

The radiance observed by a satellite sensor is determined mainly by the surface albedo and atmospheric extinction. Both atmospheric molecules (Rayleigh scattering) and aerosol particles (Mie scattering) contribute to the extinction through the atmosphere. It is relatively easy to estimate the molecular contribution, and the temporal and spatial variability of the atmospheric extinction originates mostly from the aerosol effect. The aerosol optical thickness τ_a is one of the most effective parameters in the radiative transfer process.

The radiance L_{obs} observed by a satellite sensor is given as a digital number (*DN*), *e.g.* a value between 0 and 255 in the case of an 8-bit sensor. We can define L_{obs} as a function of the *DN*, which, in turn, is related to the target albedo ρ and the optical thickness τ_a:

$$L_{obs} = f(DN),\ DN = g(\rho, \tau_a). \qquad (1)$$

Here the function f is determined from the sensor calibration, and the function g is given once the geometry of the satellite observation and the aerosol model are specified.

Figure 1 shows the relationship between ρ and τ_a calculated for Landsat-5/TM band 1. The geometry is for the image of Kanto area observed on January 14, 1999. The ρ-τ relationship is plotted for *DN* values of 50 and 60, the dominant range for band 1. This relationship has been calculated by the 6S code [4], employing three aerosol models (continental, maritime and urban) that are built in the code. From Fig. 1, it is clear that the result for the urban aerosol model is different from other two models. This is ascribable to the larger absorption coefficient incorporated in the urban model than in other models. For example, when the relative humidity is less than 70%, the single scattering albedo is 0.64 at 550 nm for the urban model, whereas it is about 0.9 for the continental and maritime models. Another important aspect found in Fig. 1 is that the difference among aerosol models appears in the region of large optical thickness. When τ_a is small, on the contrary, it is possible to retrieve the value of target albedo ρ that is more ore less independent of the aerosol model.

For the clear-sky case (no cloud), the main contribution to the aerosol optical thickness comes from the lower troposphere, especially from the boundary layer. Under such a condition, the assumption that a value of the optical thickness measured by a sun photometer (τ_{sp}) at a certain location within a satellite image represents the area is considered to be reasonable. This assumption is used here to derive the distribution of the surface albedo ρ. Hereafter this albedo distribution will be referred to as the "ρ map". In this manner, the process of the atmospheric correction is accomplished.

In the next step, this ρ map is used to evaluate the aerosol distribution from the satellite image observed on a relatively turbid day in the same season as the clear day. The functional relationship shown in Fig. 1 is used to obtain the value of τ_a from the known values of *DN* and ρ in this case. The resulting distribution of the aerosol optical thickness will be referred to as the "τ map".

2-2. Atmospheric correction

In the atmospheric correction of the clear-day image, the optical thickness is derived from the sun-photometer data (τ_{sp}) at the time of the Landsat-5 overpass. Figure 2 shows the *DN*-ρ transform function calculated by assuming three aerosol models (Continental, Maritime, and Urban) for TM band 1. The data were taken on January 14, 1999, when the aerosol optical thickness τ_{sp} was relatively small (τ_{sp}=0.1 at 550 nm). The histograms of the raw *DN* and surface albedo ρ are also shown in Fig.2. It is seen that the difference in the aerosol model does not yield noticeable change in the *DN*-ρ relationship. Thus, the surface albedo ρ derived from this method is virtually independent of the assumed aerosol model.

The precision of the albedo ρ as determined by the satellite sensors is around 10^{-3} for the 8-bit Landsat-5/TM sensor. The resolution is different for other bands, due to the inherent gain of the sensor. In general, the *DN*-ρ relationship changes with the wavelength. At shorter wavelength, a quadratic relationship holds between *DN* and ρ when ρ is small. At longer wavelength, however, a linear relationship is seen between these parameters. Since the resolution of band 2 is insufficient to retrieve the optical thickness accurately, here the result is shown only for band 1. The ρ map is obtained from the image on a relatively clear day (January 14, 1999). This ρ map is used as a reference to retrieve the optical thickness distribution in the same season (see below).

2-3. Aerosol optical thickness (τ_a map)

The distribution of aerosol optical thickness (τ_a map) is obtained as follows. For each band and aerosol model, the (ρ,τ_a) pair is calculated for each *DN* and stored in a form of a lookup table (LUT). The optical thickness τ_a can be specified by the optical thickness at 550 nm (τ_{550}), since the aerosol model dictates the dependence on the wavelength. This simulation is conducted by the 6S code, the range of τ_a being varied from 0 to 1 with a step of 0.01. In the application of the LUT, an interpolation with a resolution of 0.001 is undertaken for τ_a. Figure 3 shows the functional relationship in the LUT for the continental aerosol model calculated for the band 1 data on December 13, 1998. This image was chosen as an example with a relatively large value of the aerosol optical thickness (τ_{sp}= 0.3). For each pixel, we assume the albedo value given in the ρ map obtained from the clear-day image: thus, the aerosol optical thickness for that pixel can be determined from the pixel *DN* value using the LUT for each aerosol model. As also inferred from Fig. 3, the accuracy of τ_a can be estimated from the accuracy of ρ.

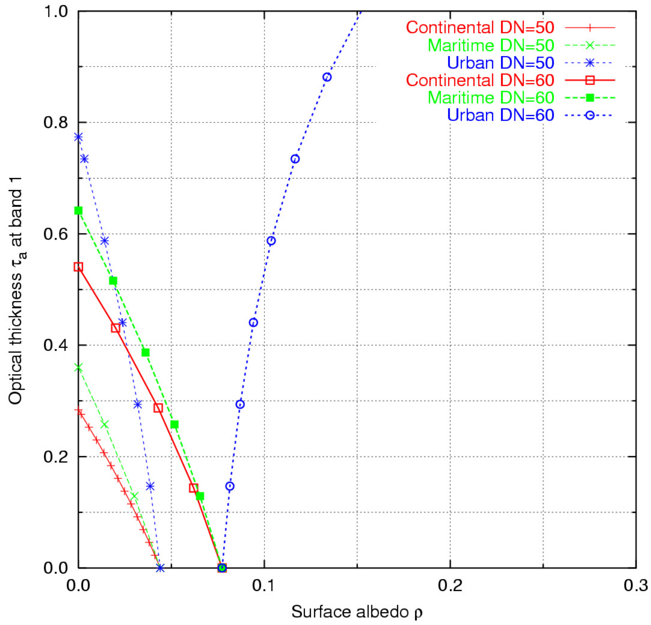

Fig. 1. The ρ-τ_a relationship for three aerosol models calculated for Landsat-5/TM band 1 image on January 14, 1999. Solid line is for Continental, dashed line for Maritime, and dotted line for Urban aerosol model. The curves are calculated for DN=50 (thin lines) and 60 (thick lines) which define the dominant DN range in the band 1 image. Urban aerosol model is characterized by a small single scattering albedo (strong absorption). When τ_a is small, the dependence on the aerosol model is insignificant.

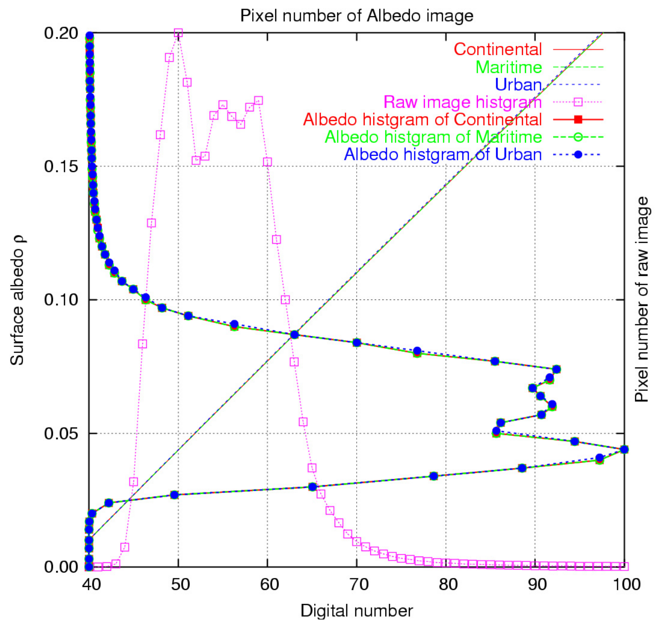

Fig. 2. The DN-ρ transformation curve for each aerosol model for a particular value of τ_a as measured by the sun photometer (τ_a=t_{sp}). Histograms of the band-1 image are shown for both DN and ρ. When the value of τ_a is small, a unique value of the surface albedo ρ can be determined regardless of the choice of the aerosol model.

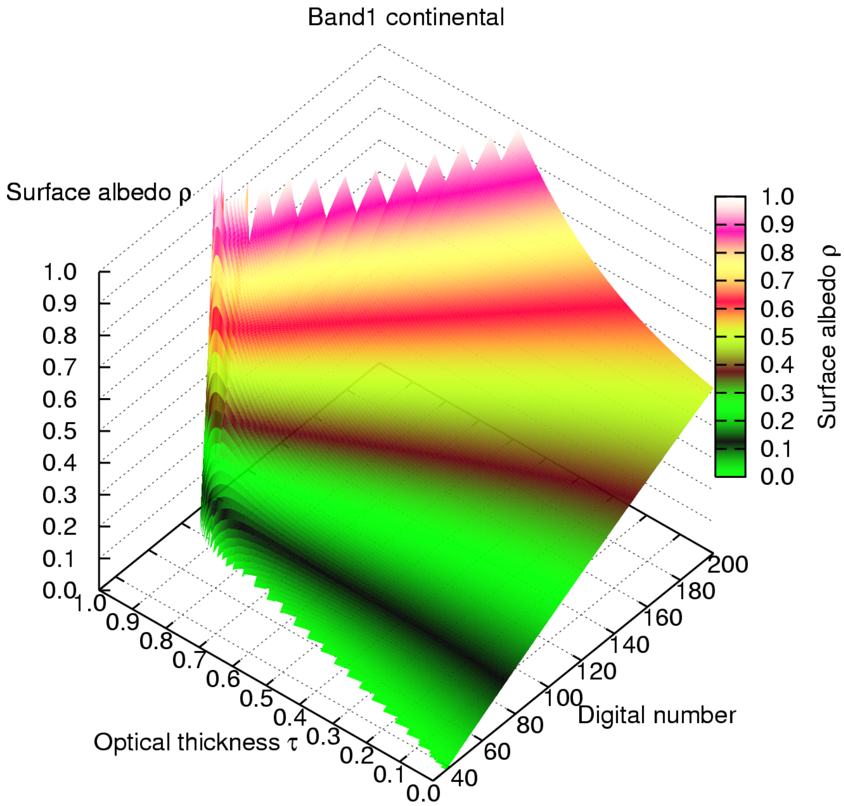

Fig. 3. The functional relationship among DN, ρ, and τ_a as calculated in a form of the lookup table (LUT). The curve is for the Continental aerosol model for the band-1 image observed on December 13, 1998.

3. Results and discussion

3.1 TM data and optical thickness

A target area chosen for the present study is a sub-scene of the Landsat-5/TM image (Path: 107, Row: 35), an image with 2001x2001 pixels centered at Chiba University (about 30 km southeast of Tokyo). The atmospheric correction is applied to a pair of datasets in the same season. First dataset is the one observed on January 14, 1999 (clear case). The correction of this dataset is used to obtain the ρ map (reference albedo map) of the winter season in the area. The second dataset obtained on December 13, 1998 (relatively turbid case) is used to derive the distribution of the optical thickness τ_a (τ_a map). For both cases, the values of aerosol optical thickness observed by the sun-photometer τ_{sp} are shown in Table 1 for band 1-4.

Table 1. Aerosol optical thickness τ_{sp} observed by the sun-photometer at 9:50 JST on each day. The values of τ_{sp} on January 14, 1999 (clear day) are smaller than those on December 13, 1998 (turbid day).

Date	Band 1	Band 2	Band 3	Band 4
Dec.13, 1998	0.294	0.241	0.192	0.140
Jan. 14, 1999	0.114	0.099	0.085	0.068

3.2 Albedo distribution (ρ map)

The ρ map (reference albedo) is derived from the data on January 14,1999. It is assumed that the values of τ_{sp} listed in Table 1 represent typical values in the TM scene. As seen from Fig. 2, more or less similar values of the surface albedo ρ can be obtained regardless of the type of the aerosol model assumed in the atmospheric correction process.

The ρ map obtained for band 1 is shows in Fig. 4 (the corresponding histogram of ρ has already been illustrated in Fig. 2). In this band, the dominant range of ρ is between 0.02 and 0.12, and these small values are mainly located in both the sea area in Tokyo Bay and inland. Pixels with high ρ values surround the Tokyo Bay, including the artificial island (named Sea Firefly) in the east side of the bay. A region with high ρ is also found in the sea area, presumably indicating the presence of haze. In order to avoid such an effect of local weather conditions, it is desirable to employ a number of images obtained on different days to construct the ρ map.

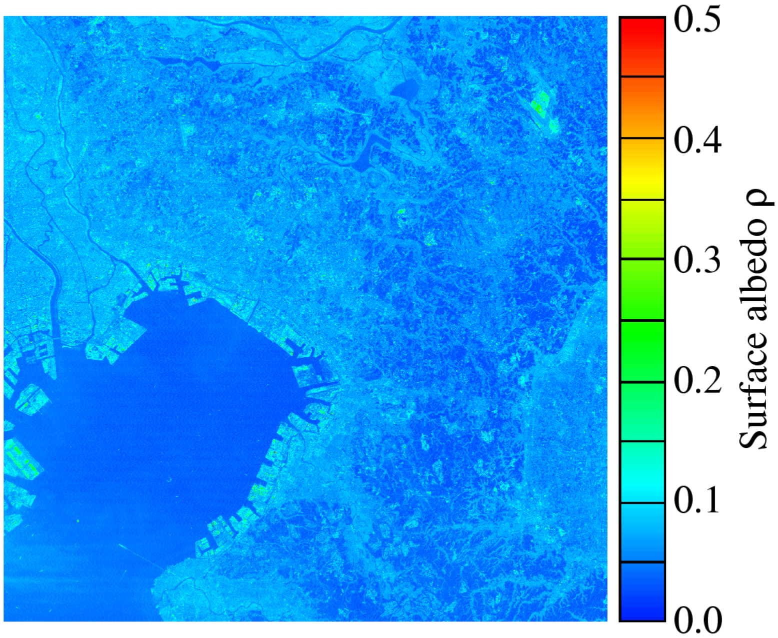

Fig. 4. Surface albedo map (ρ map) obtained from the atmospheric correction of the TM band-1 image observed on January 14,1999.

3.3 Retrieval of τ_a map

The aerosol distribution map (τ_a map) is constructed from the image observed on December 13, 1998. The aerosol models employed for this study are the continental and maritime models. Since the relationship among the parameters (Fig. 3) varies according to the model, the value of τ_a changes even if the same pair of the input parameter (*DN*, ρ) is used. The result is shown in Fig. 5, in which the value of τ_a is mapped in a range of 0 and 1: the region with τ_a>1.0 is included in the region with τ_a=1.

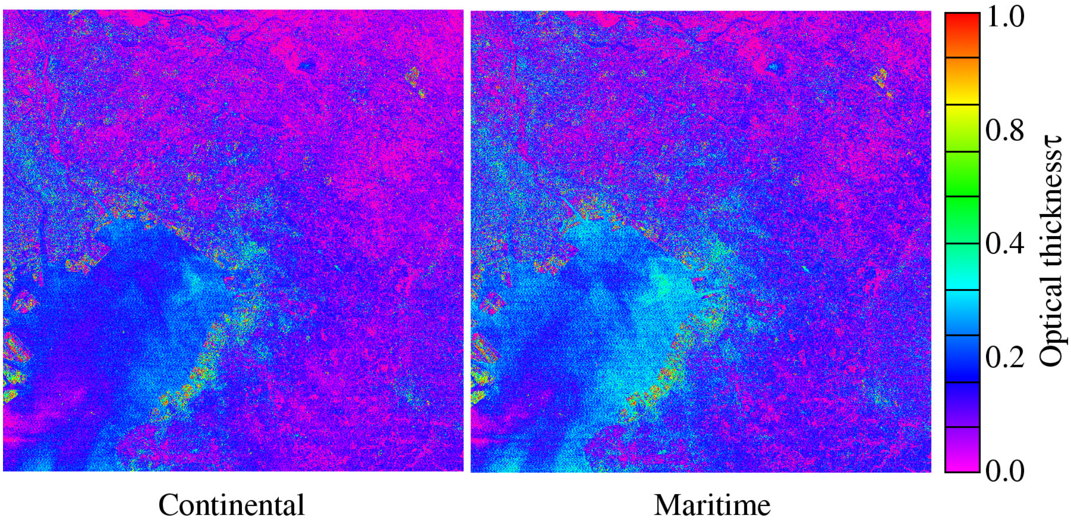

Fig. 5. Aerosol optical-thickness map (τ_a map) from the TM band-1 image on December 13, 1998.

The optical thickness over the most part of the sea area in the Tokyo Bay is found to be 0.3 or smaller. The result over the sea area is of course not free from the effect of the wind, since the albedo is dependent on the wind speed. The optical thickness is somewhat larger along the seashore. The value of τ_a is under-estimated due to the presence of haze in the lower left part of Fig. 5. On the artificial island, we obtain $\tau_a > 1$ because of large ρ. High ρ values are also found in the urban area (near the center in Fig. 5) for both aerosol models. The distribution, however, is not necessarily correlated with the ρ map. In the vegetation areas inland, aerosol loading is relatively small, though the albedo values are similar to those in the sea region. It is possible that the aerosol model may change locally. During the winter season, the northwest wind prevails due to the pressure pattern (high in west ad low in east), leading to the relative dominance of the inland (polluted) aerosols rather than the maritime aerosols.

Figure 6 shows the histograms of the τ_a distribution for band 1 and band 2. Aerosol models are continental and maritime, and the resolution of τ_a is 0.01 in the simulation. The distribution turns out to be more compact for the continental model than for the maritime model, and sparser for band 2 than for band 1. This latter feature results from the higher gain in band 2, indicating the sensor gain is also important for the retrieval of τ_a.

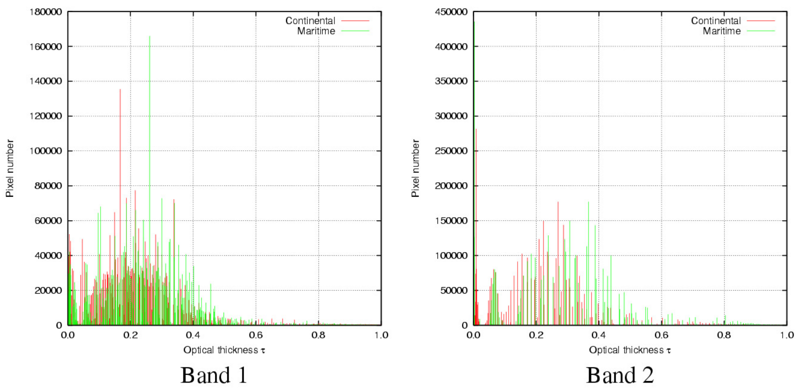

Fig. 6. Histograms of the τ_a distribution for TM band 1 and band 2.

4. Conclusions

We have discussed the derivation of the ground albedo map and the aerosol optical-thickness map from Landsat/TM data. In the determination of the ρ map (i.e. atmospheric correction), the dependence on the aerosol model is small when the optical thickness is small. This indicates that a reasonable "reference albedo map" can be retrieved using the satellite image observed on a relatively clear day. In the study of the τ_a map, on the other hand, the results are different for different aerosol models. Generally, the value of τ_a is smaller for the continental model than for the maritime model. High τ_a values are observed for the region with high albedo values. Finally, the result of this paper is developed in the Part II of this series paper [5] to further incorporate the study of aerosol size distribution from satellite data.

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