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Adaptive Contrast Stretching for Land Observation in Cloudy Low Resolution Satellite Imagery

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Abstract : Although low spatial resolution satellite images like MODIS and GOCI can be important to observe land surface, it is often difficult to visually interpret the imagery because of the low contrast by prevailing cloud covers. We proposed a simple and adaptive stretching algorithm to enhance image contrast over land areas in cloudy images. The proposed method is basically a linear algorithm that stretches only non-cloud pixels. The adaptive linear stretch method uses two values: the low limit (L) from image statistics and upper limit (U) from low boundary value of cloud pixels. The cloud pixel value was automatically determined by pre-developed empirical function for each spectral band. We used MODIS and GOCI images having various types of cloud distributions and coverage. The adaptive contrast stretching method was evaluated by both visual interpretation and statistical distribution of displayed brightness values.

Key Words : contrast stretch, MODIS, GOCI, land observation, cloud

1. Introduction

Since the range of pixel values within a satellite image is usually narrower than the full dynamic range of the sensor system, the displayed image tends to be low contrast (Jensen, 2005). Furthermore, the composition of various surface materials within a scene has also great influence on contrast of digital image display. The low contrast characteristics are very clear in optical remote sensor imagery when it contains clouds. Cloud has the highest reflected energy level in all reflected wavelengths and often leads to low contrast of entire image by obscuring other surface materials (Song *et al*., 2004). To solve the low contrast problem in image display, contrast stretching is frequently used enhancement method.

Low spatial resolution satellite imagery, like AVHRR or MODIS, have wide field of view, which enable to observe earth surface more frequently with short revisit cycle. In addition, the recently launched Geostationary Ocean Color Imager (GOCI) provides continuous images at regional scale with very high temporal resolution (Cho *et al*., 2010). GOCI imagery has about 500 m spatial resolution and is providing eight hourly observations per day during daytime. The high temporal resolution images have a great

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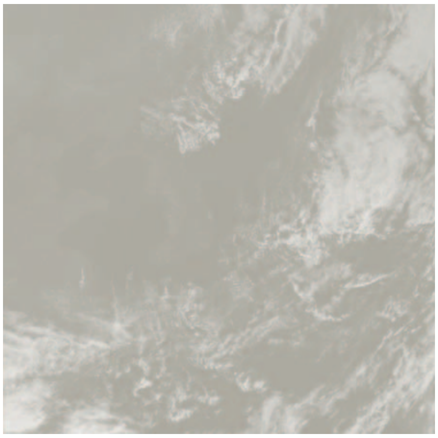
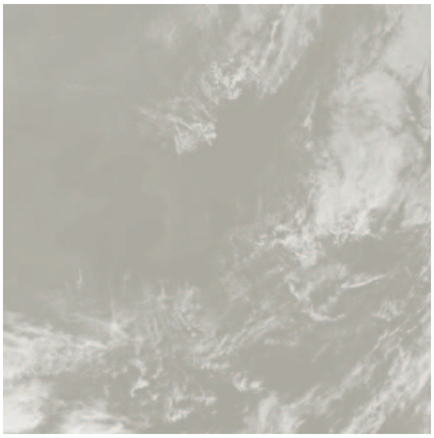


(a)



(b)

Fig. 1. Low contrast characteristics of over the land area in GOCI imagery even when it contains relatively small cloud coverage (20%): raw image display (a) and contrast enhanced image by linear stretching with minimum and maximum (b).

potential for detecting and monitoring several short-term changes over land areas (Kim *et al.*, 2011). Because of the wide swath and large geographical coverage, low resolution satellite imagery always contains more or less clouds within the scene. Because clouds usually have the highest pixel value as compared to other surface materials, it causes low contrast over land area. The low contrast effect becomes more obvious as the amount of clouds increases. For this reason, major land cover types could not be well classified even by visual interpretation (Hagolle *et al*., 2010). Fig. 1 shows the entire scene of GOCI imagery covering about $2,500 \times 2,500$ km^2 area including the Korean peninsula in center and surrounding areas. Although this image was obtained on September 22, 2011 when the cloud coverage was relatively small (20%), it obscured most land area in the image display without any contrast (Fig. 1a). Even if we applied a normal linear contrast stretching method to the GOCI image (Fig. 1b) using minimum and maximum value, it did not show much improvement from the raw image display.

There are two major categories of contrast enhancement algorithms (linear stretch and nonlinear stretch) to improve the capability of visual interpretation (Jensen, 2005). Beside the traditional image stretching methods, there have been several modifications. Kim *et al*. (2010) reported a new stretching method that was similar to piecewise linear stretch by assigning separate stretching function for each of several histogram partitions. This method was designed to enhance the contrast of entire scene and might not be effective for enhancing land area only in cloud contaminated image. In this paper, we proposed a new contrast stretch algorithm to enhance land areas only with cloudy low resolution satellite imagery. This method is particularly designed for quick and effective visual interpretation of land surface features from images like MODIS and GOCI that always contains cloud covers within the scene.

2. Method

1) Linear stretching for land area

The proposed adaptive contrast enhancement method is basically the modification of a standard linear stretch, in which the displayed brightness value

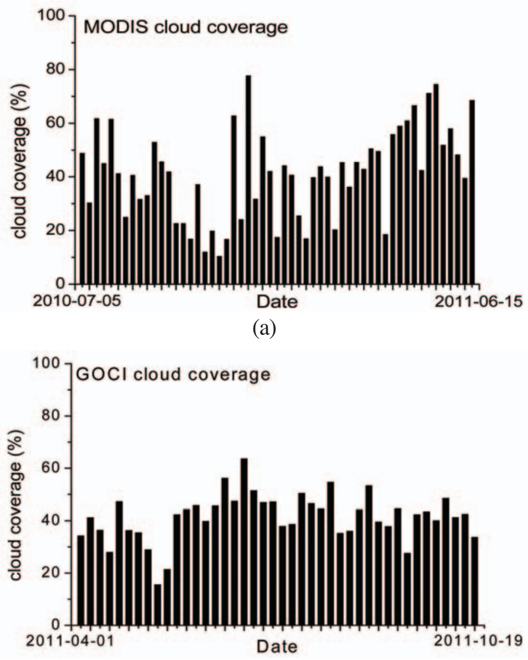
(DN_{out}) is determined by following equation.

$$DN_{out} = \left(\frac{DN_{in} - L}{U - L}\right) R \qquad (1)$$

where is DN_{in} is the original input pixel value, L and U are lower and upper limit of input pixel values to be stretched, and R is the maximum level of image display system (in most case 256). In linear stretching methods, L and U were determined by minimum and maximum values of pixels or by the mean plus and minus k times standard deviations under the assumption of normal distribution. The k is usually determined by the portions of outlier pixels to be excluded from the stretching. In our initial approach, we interactively tested the suitable values of L and U from MODIS and GOCI images to find the optimal contrast effect over lands. Although the MODIS and GOCI images include large portion of sea water within the scene, the pixel value of water is very minimal and, therefore, we used minimum value from image statistics as L. Contrast enhancement effect over land area varies by the portions of cloud coverage. To stretch only those pixels that are not clouds, the upper limit U should correspond to the value of cloud pixels. When we select U from low boundary value of cloud pixels, the contrast of the land areas enhanced significantly.

2) Histogram of MODIS and GOCI images

For this study, we used several images of MODIS and GOCI data listed in Fig. 2. We selected total 55 MODIS radiance (MOD02 product) images obtained from July 2010 to June 2011. These MODIS images were obtained by the direct link system from the National Meteorological Satellite Center and processed only for the area of whole Korean peninsula representing about 600 x 1,000 km^2 (Lee *et al*., 2008). As shown in Fig. 2(a), MODIS images have large range of cloud coverage (12.1% ~ 74.5%). The percentage of cloud cover was estimated from



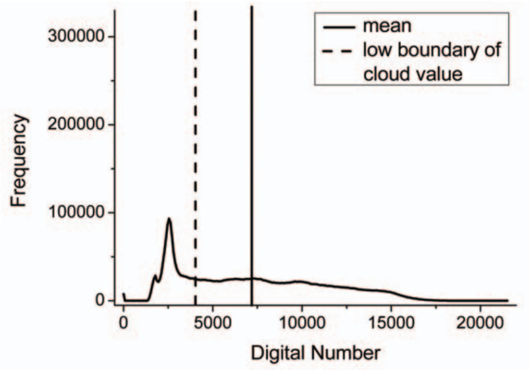
(a)

(b)

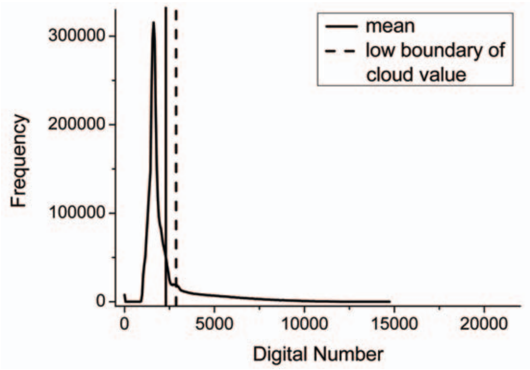
Fig. 2. Cloud coverage of daily MODIS and GOCI images used in this study.

MODIS cloud mask product (MOD35) (Ackerman *et al*., 2006). We also used 42 GOCI L1B images from April to October 2011. Unlike MODIS, GOCI image does not come with exact cloud information. Approximate cloud coverage was estimated separately for land area by the NDVI value threshold method (Remer *et al*, 2005) and for ocean by the spatial variation method (Martins *et al*., 2002; Lee *et al*., 2010). Since the geographic coverage of the GOCI image is larger than the MODIS image, variation of cloud cover is rather small (15.5% ~ 60.5%), as shown in Fig. 2(b).

The proposed adaptive contrast stretching method was designed to enhance land area only and, therefore, the stretching method should be applied only to those pixels other than cloud pixels. Since the pixel value of cloud is not fixed and varied by cloud type, thickness, and height (Ackerman *et al*., 2006), it is not always easy to determinate the low boundary



(a)



(b)

Fig. 3. Shape of MODIS band 3 image histograms of relatively high (68.6%) cloud cover (a) and low (16.8%) cloud cover (b).

value of cloud pixels. To find the low boundary value of cloud pixels (C), we checked up several images of MODIS and GOCI having large range of cloud cover. Selection of the boundary value between cloud and non-cloud pixels was relatively easy to obtain by overlaying the MOD35 cloud products. However, in GOCI image, there was no information regarding the exact boundary of cloud. We estimated approximate cloud coverage separately for the land and ocean areas and selected the low boundary of cloud pixels.

Histograms and image statistics of several images were compared. As shown in Fig. 3, histograms varied by the cloud coverage within the scene. When cloud coverage is high, the histogram shows rather wide distribution. In opposite case, the pixel values were narrowly distributed. In addition, the comparison between the mean ($\bar{x}$) and the low boundary value of cloud pixels (C) showed an interesting pattern. The C resides in left side of $\bar{x}$ with high cloud coverage while it is located in right side of $\bar{x}$ with low cloud coverage. The distance between $\bar{x}$ and C varied by the percentage of cloud coverage. Finding the relationship between $\bar{x}$ and C, we were able to extract C from $\bar{x}$. Once we are able to obtain C from the image statistics to be displayed, we could use the C value as the upper limit (U) in the contrast stretching to automatically enhance only land areas excluding cloud pixels.

3) Automatic detection of cloud pixel value

By analyzing the histograms and the locations of $\bar{x}$ and C using several MODIS and GOCI images, we found a certain relationship between C and $\bar{x}$. First, if there are no clouds the mean value of the image would be the lowest. The mean of image increases as cloud cover increases. Although the C would be somewhat constant in the same spectral band, the relative distance apart from the mean would be different by cloud coverage. Assuming that the mean is proportional to the cloud coverage, we found that the distance from C to $\bar{x}$ was inversely proportional to $\bar{x}$.

Fig. 4 clearly showed the inverse relationship between the distance from C to $\bar{x}$ and the mean ($\bar{x}$), extracted from three spectral bands of 55 MODIS images and 42 GOCI images. In three MODIS spectral bands 1, 3, 4, the coefficients of determination (R^2) of the regression equation were very strong. Using the relationship, we could directly estimate C from $\bar{x}$ for every MODIS band and used it as U in (eq. 1) for the adaptive contrast stretch for land observation. The scatter plots for three GOCI bands did not show such strong linear relationship although the inversely proportional pattern was the same (Fig. 4d, e, f). The relatively weak relationship in GOCI data might be due to the incorrect selection of cloud pixel values. There are several algorithms to detect and delineate clouds from optical satellite imagery. In MODIS imagery, the cloud boundary was delineated by the MODIS cloud mask product, which was based on an algorithm to detect cloud pixels by using both visible and thermal infrared signals (Ackerman *et al.*, 2006). On the other hands, GOCI spectral bands do not include any thermal infrared spectral bands so that the delineation of clouds might not be as accurate

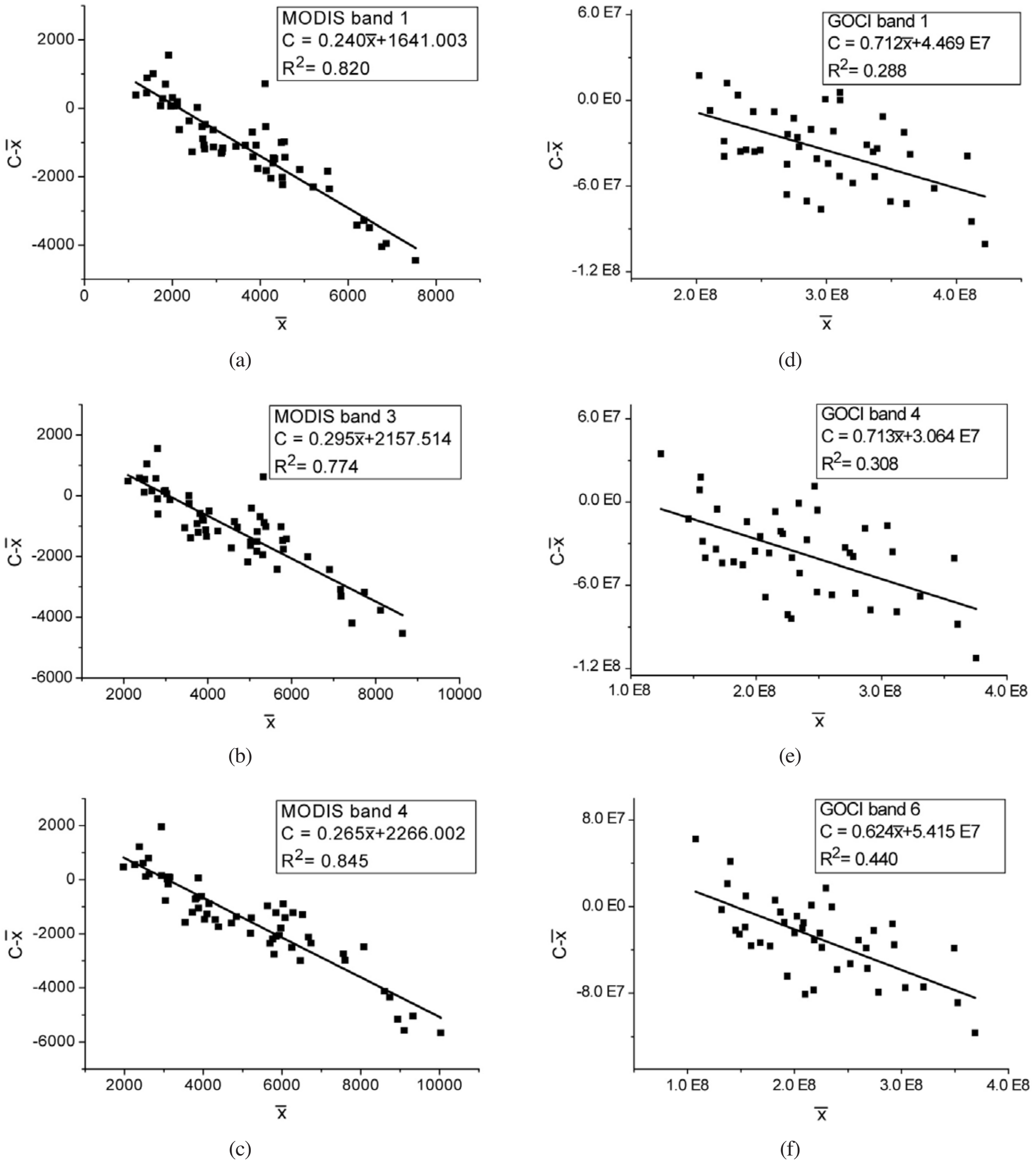


Fig. 4. Relationship between the mean ($\bar{x}$) and the distance (C - $\bar{x}$) from the low boundary value of cloud pixels (C) to the $\bar{x}$ for MODIS bands (a, b, c) and for GOCI bands (d, e, f). Using the regression equations, the upper limit (U) for the adaptive linear stretch can be directly estimated for every band.

as the MODIS. Further refinements to detect and delineate clouds from GOCI images, in particular over the land area, are needed. If we can accurately detect boundary pixels of clouds from GOCI imagery, we would have built better relationships.

3. Results and discussions

To validate the effectiveness of the proposed adaptive contrast stretch algorithm for land observation, we compared the stretched images with three other contrast stretch methods: 1) minimum-maximum (MM) contrast stretch, 2) 95 percentage linear (PL) contrast stretch where minimum and maximum are specified by mean ± 2 standard deviation, and 3) histogram equalization (HE) (Jensen, 2005). As seen in Fig. 5(a), the raw image without contrast stretch showed very low contrast and we could hardly see the land areas in the MODIS image. The MM contrast stretched images still looked very similar to the raw image, which showed almost no contrast over land areas (Fig. 5b). This is because minimum and maximum are almost identical to the range of image display levels. Even the 95 PL contrast stretched image, which has about 41% of cloud cover, showed very little improvement over lands (Fig. 5c). Highly cloud covered images tend to have a wide distribution of pixel values to the maximum, as seen in Fig. 3(a), and mean ± 2 standard deviation still include most cloud pixels within the range of stretching limit. If the image had very low cloud coverage, the 95 PL method would have shown high contrast since the mean +2 standard deviation excluded cloud pixels. Unlike the traditional linear contrast stretch, the histogram equalization showed some improvement in contrast among several surface features over lands (Fig. 5d). However, as it has been known to have over-contrast effect, the HE stretched image seemed to lose subtle details among several ground covers. The image stretched by the proposed adaptive contrast stretch showed cloud as very bright mask (Fig. 5e) since it used the low boundary value of cloud pixels (C) as the upper limit (U) in linear stretch. Major land cover types (forest, urban, bare soil, and water) were well distinguished and subtle details, like the turbid liver from the mouth of Han River and different greenness in forests, could be better discriminated with the proposed method than the HE stretch in the enlarged image of only land area in the central Korean peninsula (Fig. 6).

The contrast stretch effects on the GOCI image having 39.6% cloud coverage were about the same as the MODIS image (Fig. 7). The geographical coverage of GOCI is larger than the MODIS image and it usually contains large area of ocean (62% of entire scene). Even with large area of sea waters and cloud covers within the scene, the proposed adaptive contrast stretching result showed fine details of land surface features like desert, bare soil, grass, and forest over north China and Mongolia as compared to the HE stretched image. The stretched images between the HE and the proposed method looked similar (Fig. 7d and 7e). However, contrast stretch effects over land area was clearly better with the adaptive method than with the HE method, when we displayed only the land area over northern part of China and Mongolia where several ground cover types mixed with a little tonal difference (Fig. 8).

In addition to the visual interpretations, quantitative comparison was also made to evaluate the contrast stretch effects over land area. Table 1 showed the mean and standard deviations of the displayed brightness values after applying different stretching methods on both MODIS and GOCI images. Because the proposed algorithm was developed to enhance only land area, we calculated

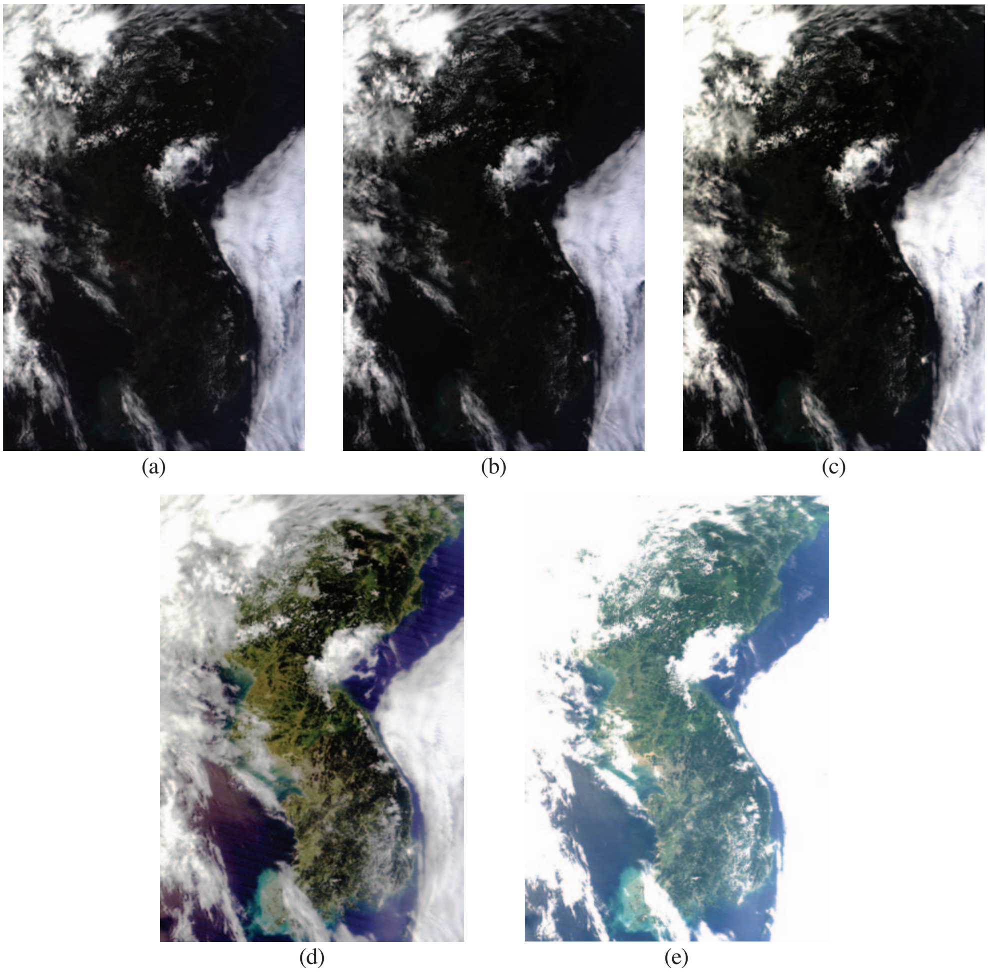


Fig. 5. Comparison of contrast stretch methods over lands with MODIS color composite image (RGB-band1, 4, 3) obtained on July 20, 2011: (a) raw image, (b) minimum-maximum contrast stretch, (c) 95% linear (PL) contrast stretch, (d) histogram equalization stretch, and (e) the proposed adaptive contrast stretch.

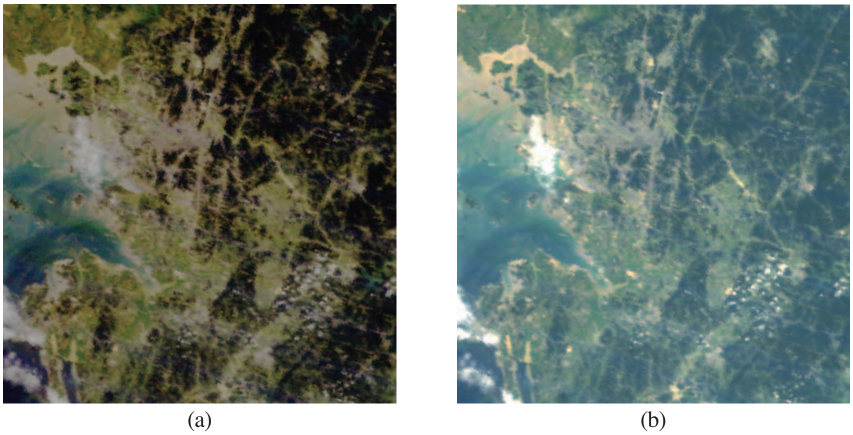


Fig. 6. Enlargement of contrast stretched MODIS images between histogram equalization stretch (a) proposed adaptive contrast stretch (b) over the central Korean peninsula.

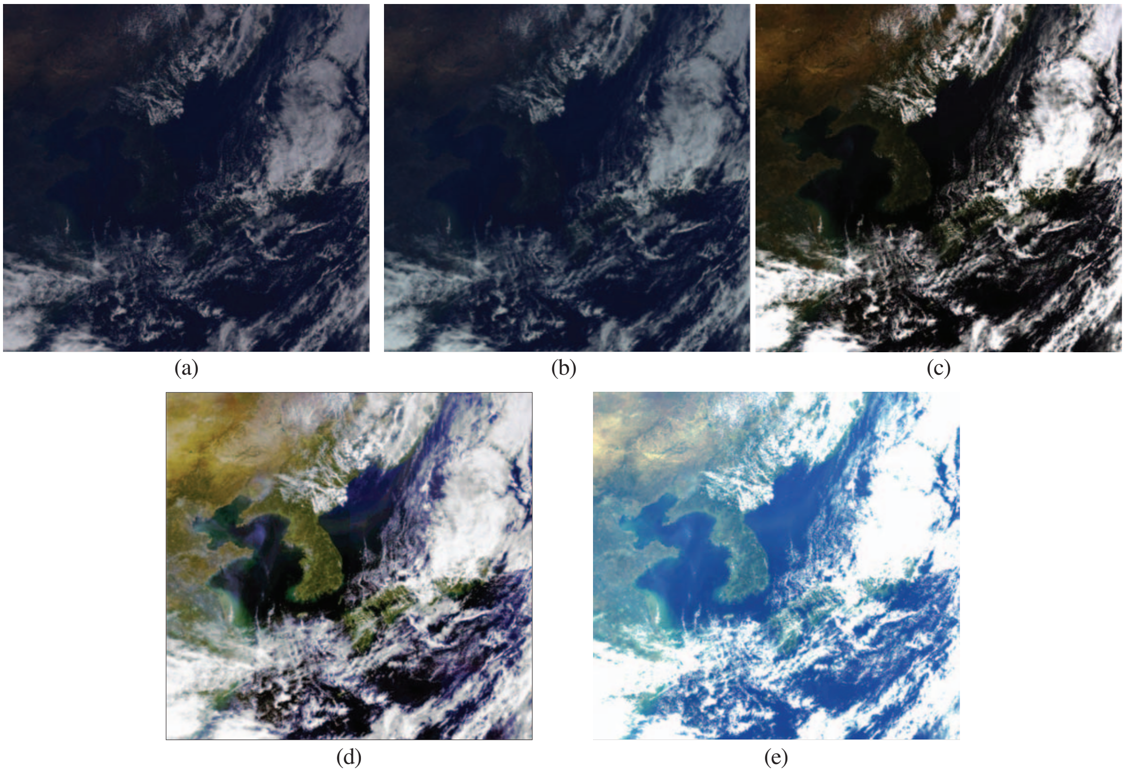


Fig. 7. Comparison of contrast stretch methods with GOCI color composite image (RGB-band 6, 4, 1) obtained on September 22, 2011: (a) raw image, (b) minimum-maximum contrast stretch, (c) 95% linear (PL) contrast stretch, (d) histogram equalization stretch, and (e) proposed adaptive contrast stretch.

Fig. 8. Enlargement of contrast stretched GOCI images between histogram equalization stretch (a) proposed adaptive contrast stretch (b) over the northern China and Mongolia.

the statistics from the almost cloud-free land area. In general, contrast stretched images would have higher standard deviations than the raw image. The displayed brightness values were expanded significantly (high standard deviation) in both HE and the proposed adaptive methods. The proposed method showed the highest standard deviations with exception in MODIS band 3 and GOCI band 1, which were both blue wavelength bands. Since HE equalization method used full range of original pixel

Table 1. Mean and standard deviations of displayed brightness values for relatively cloud-free land areas after applying contrast stretch methods on MODIS and GOCI images

	MODIS						GOCI					
	Mean			standard deviation			Mean			standard deviation		
	band1	band 3	band 4	band 1	band 3	band 4	band 1	band 4	band 6	band 1	band 4	band 6
raw	6.00	8.96	10.02	5.99	5.78	7.50	25.37	18.16	13.19	2.71	4.03	5.13
MM	8.14	12.08	10.49	15.67	17.56	16.60	43.15	27.24	23.34	4.70	6.34	9.50
PL	24.36	23.09	23.96	36.39	34.43	36.03	16.62	33.34	39.13	11.07	13.91	19.78
HE	87.41	74.33	89.60	58.74	61.25	56.50	98.38	129.87	132.90	39.08	25.82	28.58
Proposed	129.45	155.27	154.68	72.30	55.97	58.77	168.93	156.51	119.16	17.83	31.82	45.36

values, which included some signal from large areas of water and also cloud, the high standard deviation would not be surprising. From both visual interpretation and standard deviation comparison, the proposed adaptive method showed as an effective tool to enhance contrast over land areas in cloud contained low resolution satellite imagery.

Although the proposed method showed better contrast effects to visually enhance over land area, it might have a certain limitation when there were other land covers that had high pixel values like clouds. For instance, snow has high reflectance that is about the same as clouds in visible and near infrared wavelengths. Therefore, if some portions of lands are snow-covered during the winter they would be seen just like cloud, in particular with GOCI images having spectral bands only in visible and near infrared wavelengths.

4. Conclusions

In this study, we proposed a simple and adaptive contrast stretching method for land observation in MODIS and GOCI imagery that had consistent cloud covers. The proposed algorithm is basically a linear stretch method that stretches only non-cloud pixels. Because clouds usually have higher pixel value than other land cover types, we developed a method to determine the low boundary value of cloud pixels for each spectral band of MODIS and GOCI imagery. The low boundary value of cloud pixels, which would be used as an upper limit in the linear stretch, was automatically determined by the mean of the image. The proposed contrast stretching method was very effective to enhance contrast effects when we compared it with other traditional methods in both visual interpretations and statistical analysis of the displayed brightness values.

Of course, there is an interactive contrast stretching method, which adjusts histogram manually, to display the enhanced image over land area. However, the interactive contrast stretch method is often slow and tiresome to apply. The proposed method was designed to have contrast stretched image automatically by using only image statistics. From the empirically derived equation to estimate low boundary value of cloud pixels (C) from the mean of each spectral band image of MODIS or GOCI, it automatically determines the upper limit of the linear stretch. Once the empirical relationships between C and $\overline{x}$ determined, the proposed method can be easily implemented along with other traditional contrast stretching method. The determination of C value is somewhat empirical, in which a prior function to estimate C should be determined for each spectral band from several images having larger range of cloud coverage. Developing the regression equation for every bands of each sensor type would be difficult and sometimes subjective during the selection of cloud pixels. Considering that reflected signal from clouds has large range of variation due to the cloud type and thickness, further study is needed to define the exact boundary of clouds for this contrast stretch algorithm over land observation.

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