Effective Compositing Method to Produce Cloud-Free AVHRR Image

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***Abstract*—The Advanced Very High Resolution Radiometer (AVHRR) series of instruments have been frequently used for land cover change and global environment studies. The availability of more than 30 years' records have made important time-series studies possible. Removing cloud effects from AVHRR images is a critical task when using the data to monitor land cover changes. Considering that the maximum normalized difference vegetation index (NDVI) compositing method is not suitable for land cover types with low NDVI (e.g., water, snow, and bare ground), we propose a new compositing method to remove cloud effects while keeping information of all land cover types. The developed method includes three steps: 1) compositing daily AVHRR images using maximum brightness temperature in Channel 4; 2) replacing water pixels with pixels having maximum Channel 1/Channel 2 ratio; and 3) replacing vegetation pixels with pixels having maximum NDVI. The proposed method was tested on the Land Long-Term Data Record-AVHRR dataset in a region of 37°E–180°E, 3°S–73°N in 1993 to generate monthly minimal cloud-effected images. After compositing, the average ratio of cloud-contaminated and invalid pixels is reduced from 64.8% to 22.0%. Compared with the other two methods (composite using maximum NDVI and composite using cloud masks), our method is shown to be more effective and convenient. Moreover, the compositing process takes consideration of the temporal profile of land surface, which is suited for long time global or continental land cover change studies. Composite images generated in different time periods are also evaluated to identify the proper compositing period.**

***Index Terms*—Advanced Very High Resolution Radiometer (AVHRR), cloud effects, compositing method, compositing period.**

I. Introduction

The Advanced Very High Resolution Radiometer (AVHRR) is the only source of remotely sensed data that includes continuous global coverage since 1981. More than 30 years' consistent and quantitative data are an invaluable and irreplaceable archive of historical land surface information [1], providing appropriate remote sensing data for long time global-scale or continental-scale studies of land-based global change processes [2].

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Reducing cloud effects is a critical issue in the analysis of AVHRR data, since average 64% of the earth's surface is obscured by clouds on any single day [3]. For long time-series global or continental studies, the providing of cloud-free AVHRR images is of great importance to land cover classification.

The compositing techniques can produce cloud-free images from individual partly cloudy input scenes by selecting cloud-free pixel for the same geographic location from images taken over a limited period of time. Cloud-free pixel selection is typically performed by using either maximum value compositing (MVC) or by using spectral tests to predetermine the probability of cloud contamination for each pixel before compositing [4].

For MVC, one popular criterion is using maximum normalized difference vegetation index (NDVI). Most researchers rely on NDVI to obtain cloud-free image [5]. The algorithm is based on the theory that for a given pixel over land, a higher NDVI usually indicates a lower cloud fraction. On a per-pixel basis, the pixel with the maximum NDVI in the month is chosen for compositing [4]. However, this method fails over water and snow/ice surfaces, due to their negative NDVI values; it may also fail over rock and bare soil surfaces, due to their near-zero NDVI values.

As for compositing using cloud masks, cloud masks are first generated by cloud detection schemes, and then clear pixels are picked out according to the cloud masks. Some improved methods are based on cloud masks with combination of other criteria [4], [6]. Cloud detection schemes mostly apply a series of spectral and spatial thresholds to the measured radiometric observations of each pixel [2], [7], [8]. They may be different according to the properties (band settings and spatial resolution) of remotely sensed images. Some of them make use the reflectance temporal variations based on multi-temporal observations, or the covariance between cloudy and clear images [9], [10]. The result of final cloud-free composite is highly dependent on the accuracy of cloud masks. This method is not so well-suited to process large volume of data required for long time-series studies because of the intensive work load of flagging cloudy for every pixel from each image and then picking up clear pixel from an array of clear pixels.

In this letter, we propose an effective compositing method to produce cloud-free images. The method emphasizes on retaining all land cover information without complex threshold settings, and, the most importantly, the compositing process takes into account of radiometric temporal profile of land surface. As a result, the composite is well suited for long time-series global or continental studies.

II. Data Source and Study Area

AVHRR on the National Oceanic and Atmospheric Administration (NOAA) polar orbiting satellites senses a red (0.58–0.68 μm, Channel 1), a near-infrared (0.725–1.10 μm, Channel 2), a mid-infrared (3.55–3.93 μm, Channel 3), and two thermal (10.5–11.3 μm and 11.5–12.5 μm, Channels 4 and 5) and spectral channels (the AVHRR/2 configuration). Starting with the AVHRR/3 on NOAA-16, launched in 2000, the sensor operation alternated between bands centered on 1.6 μm (Channel 3a) during the day and on 3.75 μm (Channel 3b) during the night, disrupting continuity, but the historical configuration returned in May 2003 when NOAA-16 again operated Channel 3b continuously [11].

Version 3 of Land Long-Term Data Record (LTDR)-AVHRR products in 1993 are used as test data in the study. The products are generated after radiometric calibration, geometric and atmospheric correction [11]. The daily surface reflectance data uses geographic projection at a resolution of 0.05° (approximately 5 km).

The study area is located at 37°E∼180°E, 3°S∼73°N, a region including diverse land cover types, such as vegetation, bare ground, water, snow, and ice. It has a wide range containing over 4.3 million pixels, which could be used to test the effectiveness of the proposed method. According to the detection result of cloud screening algorithm CLAVR-1 (Clouds from AVHRR-Phase I), average ratio of cloudy and invalid pixels on daily AVHRR scenes in this region is 64.8%, which may jeopardize the accuracy of any quantitative analysis. Based on the above reasons, the cloud effects should be reduced before the use of the dataset.

III. Method

Selection of cloud-free pixels from component images is critical to the success of a compositing method. Three steps of selecting least cloud-contaminated pixels are described in this section. We assume that the basic land cover type at the same geographic location does not change in a month even though the growing vegetation class might change during the summer season.

It has been acknowledged that clouds are generally bright in the visible spectrum and cold in the thermal channels. Previous studies showed that the brightness temperature values in Channels 4 and 5 are strongly correlated for each land cover type [8]. Most studies used Channel 4 for cloud detection instead of Channel 5 because AVHRR data received from NOAA-6, -8, -10, and -12 have not spectral information of 11.5–12.5 μm. Besides, mid-infrared Channel 3 is noisy in several images [12]. Channel 1 contains high reflectance for most clouds and low reflectance for most land areas, except for snow, white sand, and ice. In conclusion, reflectance in Channel 1 (Refl 1) and brightness temperature in Channel 4 (T4) are of high values in discriminating clear land surface from clouds.

In Fig. 1, Refl 1 and T4 are plotted for each of the four land cover types (barren, snow, vegetation, and water) within July 1993. Four points (each point per land cover type) are sampled on everyday's AVHRR scene at the same location. Each point within a month is under conditions of no clouds, cloud-shadow, or clouds. Fig. 1 illustrates that the cloudy pixels generally have high reflectance in visible spectrum and low temperature in Channel 4 over all land cover types. But it is difficult to select clear (cloud-free) pixels using visible band because it is hard to exclude cloud shadow effects. Most cloud-free pixels have higher reflectance than cloud-shadowed pixels, but for those with low reflectance, the situation is different. In addition, clear pixels have large reflectance range, and the differences between the reflectance of thin-cloud/cloud-shadowed pixels and clear pixels are not significant, which also adds to the difficulty of selecting clear pixels in visible bands.

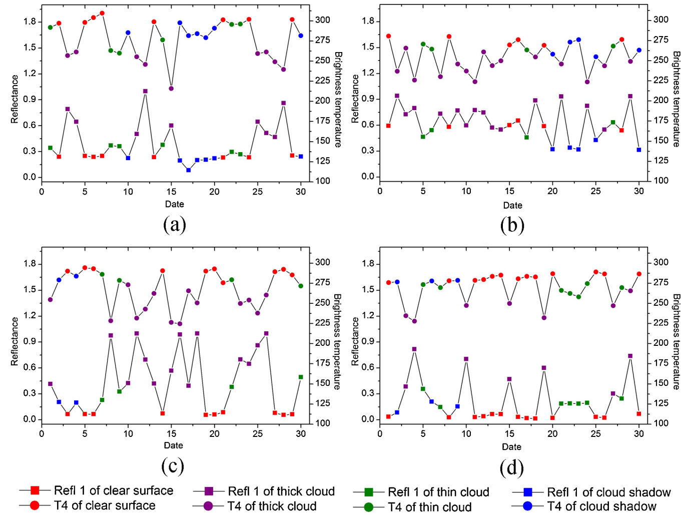

Fig. 1. Reflectance in Channel 1 (Refl 1) and brightness temperature in Channel 4 (T4) of sampled pixels for four land cover types within a month. Pixels covered with no clouds, cloud-shadow, or clouds within a month are using different colors. (a) Barren. (b) Snow. (c) Vegetation. (d) Water.

However, for almost all land cover types, clear pixels have the highest T4 within a month. Cloudy have lower T4 because clouds are composed of cold particles, such as large ice crystals. T4 of cloud-shadowed pixels are also lower because the pixels receive less sunlight. In summary, T4 is lowest for cloud, highest for clear land, and medium for cloud shadow.

A. Compositing Using Maximum T4

The analysis above illustrates T4 can serve as an important index for discriminating cloud-free pixels from cloud-contaminated ones. Pixel with highest T4 is least affected by clouds and cloud shadows. Thus, for every pixel, five channel values associated with maximum T4 are selected from a month's AVHRR scenes to generate a composite image C1 for the first step (Step A). Compositing using maximum T4 obtains good results over large areas, but it misidentifies some clear pixels with very low temperature. Some clear water or vegetation at high latitude have lower T4 than thin cloud, haze, cloud shadows, or smoke (e.g., caused by forest fire). As a result, these clear pixels are missed by compositing using maximum T4, and cloudy pixels are erroneously selected. Therefore, supplementary processing is added to remove the cloud effects over some water and vegetation areas.

B. Replacing Water Pixels With Pixels Having Maximum Channel 1/Channel 2 Ratio

The second step (Step B) aims at retrieving clear water pixels because composite image C1 may lose water information. Clear water has higher reflectance in Channel 1 than Channel 2, and cloud over water has opposite reflection characteristic. Consequently, the largest Channel 1/Channel 2 ratio is appropriate for selecting cloud-free water pixels from input AVHRR scenes. In this step, we obtain a composite image C2 by choosing pixels with the largest Channel 1/Channel 2 ratio. Then select clear water pixels from image C2 to replace the pixels at the same location in image C1. In this way, the replaced image is generated after Step B, marked as C1′.

Water has very low reflectance both in Channels 1 and 2, and also has higher reflectance in Channel 1 than Channel 2, so it is easily to be separated from other objects in image C2 (e.g., clouds, barren, both have high reflectance). Here, pixels meeting the following conditions are deemed as clear water pixels: 1) Refl 1 (reflectance in Channel 1) > Refl 2 (reflectance in Channel 2); 2) Refl 1 < 0.2 and Refl 2 < 0.1. Five hundred points of water (including shallow/deep inland water and moderate/deep ocean) are sampled to determine the appropriate threshold, it is found that more than 90% of the pixels have reflectance in this range. The thresholds are appropriate for detecting both clean water and water containing high sediment.

C. Replacing Vegetation Pixels With Pixels Having Maximum NDVI

The third step (Step C) is to recover some vegetation information. It is well recognized that maximum NDVI compositing way can greatly remove cloud effects over vegetation because clear vegetation usually has higher NDVI than cloudy and cloud-shadowed vegetation [5]. Pixels with the maximum NDVI are selected to generate a composite image C3. In order to keep the maximum vegetation information in the final composite image, pixels with NDVI greater than the threshold T_{NDVI} in image C3 are selected to replace pixels in image C1′. After replacement, image C1″ is generated as the final composite.

NDVI less than 0.2 can be considered as bare soil [13] and the 0.2–0.3 NDVI value is a representative value for very low vegetation areas. It is found that vegetation having NDVI below 0.3 might also be contaminated by thin clouds, for these areas, maximum T4 compositing result is more accurate. The T_{NDVI} is set to 0.3 in this letter.

Because some cloud-contaminated vegetation pixels (vegetation covered by cloud edge or thin cloud) may have higher NDVI than clear vegetation, some adjustments are made to the maximum NDVI compositing procedure to ensure the right selection of clear vegetation pixels. According to vegetation's reflectance in AVHRR calculated from spectra obtained from the USGS spectral library, its reflectance is < 0.14 in Channel 1 and >0.2 in Channel 2 [14]. The following two types of vegetation pixels, which are not consistent with vegetation spectral reflectance characteristic, will not participate in the maximum NDVI compositing process: 1) Refl 1 > 0.14 (covered with cloud) and 2) Refl 2 < 0.2 (covered with cloud shadow). These criteria are helpful to eliminate cloud-contaminated vegetation pixels by excluding these pixels from the composite process.

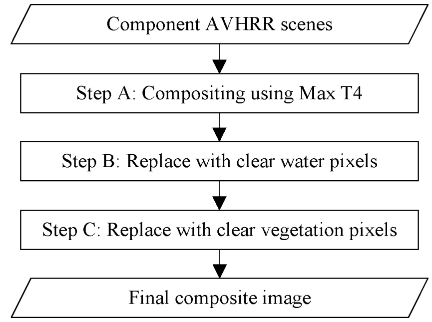

Fig. 2. General flowchart of producing cloud-free composite from daily LTDR-AVHRR scenes.

D. Compositing Result

Monthly composite is generated using 30 consecutive days' AVHRR images in every month. It costs about 10 min to produce a composite of the study area. It is implemented on the remote sensing software ENVI + IDL. A laptop computer running Microsoft Windows 7 (64 b) with 2.4 GHz Intel Core 2 processor and 4 GB RAM is used for the test. Fig. 3 shows part of the study area in July 1993. The area is located in Central Asia, including Taklimakan desert, Tianshan Mountain, Junggar Basin, and Qinghai-Tibet Plateau in China, as well as the border of Pakistan, Kazakhstan, Kyrgyzstan, Tajikistan. The region contains various land cover types, such as vegetation, snow, water, and bare ground. In Fig. 3, blue-white pixels are cloud covertures. The color for ice and snow is aquamarine blue because they have the similar feature as clouds, however, they only appear in the alpine region (e.g. Tianshan Mountain and the Qinghai-Tibet Plateau).

Fig. 2 shows the structure of our method. The Step A, described in Section III-A, involves choosing pixels with the highest T4, relying on the fact that tropospheric cloud is usually colder than the underlying surface. The image after Step A is shown in Fig. 3(a). It can be seen that most clouds are removed after compositing using maximum T4, but some water information is lost (almost all the lakes on the Qinghai-Tibet Plateau have disappeared) because thin cloud over water sometimes has higher temperature than clear water. Step B, stated in Section III-B, selects clear water pixels from maximum Channel 1/Channel 2 ratio composite, and then to replace these areas with values generated in Step B. By this stage, water information is retrieved, as shown in Fig. 3(b). In Step C, stated in Section III-C, replacement is implemented to maintain that maximum vegetation information in every month. Clear vegetation pixels are generated by maximum NDVI compositing way adding into strict filtering criteria. Comparison between Fig. 3(b) and Fig. (c) shows that Fig. 3(c) is greener and more parts in Fig. 3(c) are covered by vegetation.

IV. Assessment

The proposed method is compared with compositing using maximum NDVI and cloud masks through visual interpretation and quantitative analysis.

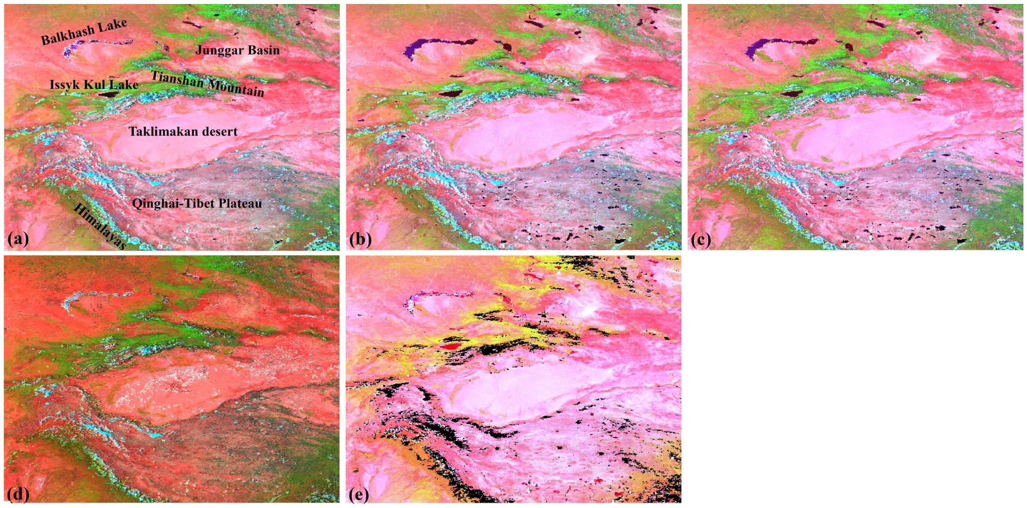

Fig. 3. AVHRR images in Central Asia, July 1993, Channel 1 in blue, Channel 2 in green, Channel 3 in red. (a) Composite image after Step A of proposed method. (b) Composite image after Step B. (c) Composite image after Step C (the final composite result using proposed method). (d) Composite result using maximum NDVI. (e) Composite result using cloud masks.

A. Comparison With Compositing Using Maximum NDVI

When compositing by maximum NDVI, cloudy pixels are masked out by using a Channel 5 thermal threshold of 0 °C for all continents except Africa, where a cloud mask of 10 °C is used [1]. The result is shown in Fig. 3(d). It can be clearly seen that Balkhash Lake, Issyk Kul Lake, some areas of Taklimakan Desert are covered with clouds, because NDVI of water and bare soil are similar to or even smaller than that of clouds. Compositing uses maximum NDVI does not perform effectively on other land cover types except for vegetation, however, the proposed method is suited for these areas, as shown in Fig. 3(c).

B. Comparison With Compositing Using Cloud Masks

Cloud masks are generated by CLAVR-1 cloud detection algorithm in this letter, because it is the most widely used cloud detection algorithm. The algorithm classifies 2×2 pixel arrays into clear, mixed, and cloudy categories [7]. In our assessment, cloudy, mixed cloudy, and cloud-shadowed pixels are all classified as cloud-contaminated ones. During the compositing, for every position in an image, the first clear pixel in that month is picked out and stored in the final composite. The composite result is shown in Fig. 3(e). There are many gaps in the result [black pixels in Fig. 3(e)] that means these regions are flagged as cloudy all the month and no clear pixel can be picked up for compositing. It occurs due to the inadaptability of the CLAVR-1 algorithm on some areas (lake, permanent snow/ice regions). The compositing using cloud masks is highly dependent on the cloud detection algorithm. If the cloud screening algorithm is too strict, some clear pixels are flagged as cloudy, resulted in gaps in the composite image (because no clear pixels within a month); if it is too lax, some cloudy pixels are flagged as clear, resulted in many cloudy pixels existing in the composite.

C. Quantitative Analysis

Although CLAVR-1 algorithm's inadaptability over some areas, it is still valuable to quantitatively evaluate the composites using different methods. Cloud cover percentages (ratio of cloud-contaminated pixels to the total pixels in the image) in composites are computed by CLAVR-1 algorithm. Missing pixels in the composite using cloud masks are counted as cloudy pixels in statistics. Maximum NDVI compositing method fails over water surface, thus ocean areas does not take part in the statistics. Cloud percentage in January, February, November, and December are not involved due to: 1) areas at high latitude in winter are normally covered by snow and ice and CLAVR-1 algorithm fails over these areas and 2) pixels at high latitude usually do not have values in winter, e.g., pixels at latitude 70°N do not have data until February 15, 1993 and lose data again after October 27.

TABLE I

CLOUD COVER PERCENTAGES IN THREE COMPOSITES

Months	Composite using proposed method (%)	Composite using maximum NDVI (%)	Composite using cloud masks (%)
March	39.38	54.87	50.59
April	21.82	42.17	36.26
May	15.15	29.05	27.25
June	13.79	19.94	15.32
July	11.57	18.53	17.42
August	11.47	17.85	15.74
September	13.21	17.94	15.45
October	23.54	34.57	36.97
Average	18.74	29.37	26.87

Table I shows cloud cover percentages in three composites using three different methods. According to Table I, the annual average residual cloud cover percentage in the composite result is 18.74% using proposed method, less than that of using other two compositing methods.

Actually, the cloud cover percentage in composite result is lower than that indicated in Table I. When examined by visual interpretation, it is found that some cloud-free pixels are flagged as cloudy. That is partly due to the inadaptability of CLAVR-1 algorithm over some areas. And, we classify those mixed-cloudy pixels into cloud-contaminated class, which will also make cloud cover percentage much higher than the reality situation.

TABLE II
CLOUD COVER PERCENTAGES OF DIFFERENT PERIOD COMPOSITES

Months \ Percentage	Compositing Period		
	10-day	15-day	20-day
Mar.	47.53 %	49.48 %	42.75 %
Apr.	37.65 %	32.44 %	29.41 %
May.	20.14 %	18.08 %	16.80 %
Jun.	14.97 %	13.68 %	15.24 %
Jul.	14.80 %	12.84 %	13.46 %
Aug.	14.13 %	11.44 %	12.08 %
Sep.	14.20 %	13.25 %	12.90 %
Oct.	24.82 %	24.73 %	23.31 %
Average	23.53%	21.99%	20.74%

Those cloudy pixels in the final composite image are also examined by looking back at the daily LTDR-AVHRR scenes. It is found that these pixels are cloud contaminated in the whole month. Cloud effects on these pixels cannot be removed because no cloud-free pixels can be picked up for compositing.

D. Compositing Period Analysis

It has been estimated that compositing daily AVHRR images over a ten-day or bi-weekly time period could remove most cloud effects [1], [15]. In order to identify the proper compositing period, results composited by 10, 15, and 20 consecutive days' images are evaluated. Table II shows cloud cover percentage of different-period composites. It indicates that average cloud cover percentage of 10-day composite is 23.53%. It is not adequate to remove most cloud effects. Cloud cover percentage does not show significant difference between 15- and 20-day composites, but 20-day composite is much better for removing cloud effects though visual interpretation. It is suggested that to use more than 15 days' AVHRR images to generate a monthly composite image.

V. CONCLUSION AND DISCUSSION

In this letter, an effective compositing method was developed to get monthly cloud-free AVHRR images. A three-step algorithm was used to select cloud-free pixels from daily AVHRR images. The proposed method was tested on AVHRR-LTDR dataset in 1993. Visual interpretation and quantitative analysis demonstrated that this method performed well on removing cloud effects over all land cover types at any latitude in every month. In addition, the method also eliminated some spurious high values (invalid data, e.g., data transmission errors) and filled gaps in original AVHRR scenes at the same time by excluding these pixels from participating in the compositing procedure. The maximum NDVI information was kept for vegetated areas and maximum brightness temperature was kept for nonvegetated areas in every month, which preserved the uniform temporal profile that is critical for land cover change studies, because land surface temperature temporal profile and the metrics derived from NDVI were the most robust metrics for classing land cover types [16]. The proposed method maintained clear land surface information at a maximum extent, however, it could not guarantee that all pixels in composite image were cloud-free. It eliminated cloud effects in large areas except for areas covered by clouds all the month (e.g., some area in southwest China). Cloud screening was required if residual cloud-contaminated pixels to be eliminated, but the work was much less comparing to detecting clouds on huge amounts of daily AVHRR images. This method has only been tested on AVHRR-LTDR dataset, but it showed great potential of being applied to other datasets, such as AVHRR Pathfinder dataset or MOD09CMG data acquired from MODIS platforms. The further study was given focus to removing residual cloud-contaminated pixels in composite images. It was planned to use algorithm to detect cloud-contaminated pixels, and then to replace these pixels with interpolated values from adjacent months or adjacent years or combination of the two of them.

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