Rainfall Retrieval and Nowcasting Based on Multispectral Satellite Images.  
Part II: Retrieval Study on Daytime Half-Hour Rain Rate

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ABSTRACT

To implement continuous and reliable rainfall retrieval, based on the satellite retrieval algorithm of 10-min rain rate, this study proposes an immediate tracking and continuous accumulation technique (ITCAT) of half-hour rainfall retrieval by further combining the cross-correlation method. The ITCAT includes two steps.  
1) The cross-correlation method is applied to track cloud-motion currents and establish 10-min-interval image sequences.  
2) A continuous retrieval of 10-min rain rates is conducted with the image sequences, and finally a total half-hour rainfall is determined by accumulations. The satellite retrieval tests on the typical precipitation processes in the summer of 2008 show that, compared with the previous direct rainfall retrieval for half-hour to one-hour, this rainfall retrieval technique significantly improves the retrieval accuracy of rainfall scope and rainfall intensity ranging from slight rain to rainstorm for both real-time monitoring or nowcasting processes. This technique is more effective than the previous algorithm, and the fundamental reason lies in its consideration of the movement of cloud clusters. On this basis, coverage duration of rainfall clouds can be reliably estimated. It is of significance to the retrieval of deep convective cloud rainfall with rapid movement speed and drastic intensity variation. This technique also provides a feasible idea for improving the accuracy of rainfall nowcasting.

1. Introduction

In the first part of this study (Zhuge et al. 2011, hereafter Part I), the method of using geostationary meteorological satellites for the retrieval of daytime 10-min ground rainfall field was introduced in detail. First of all, the rainfall probability identification matrix (RPIM) is used to distinguish rainfall clouds from nonrainfall clouds. Then, the multispectral segmented curve-fitting rainfall algorithm (MSCFRA) is used for estimating the 10-min rain rate of the determined rainfall areas according to infrared (IR) brightness temperature and visible (VIS) albedo.

The half-hour or one-hour rainfall measured at a certain observation station mainly depends on the following two aspects (Follansbee 1973; Griffith et al. 1978): 1) the rain rate within this period and 2) the coverage duration of rainfall clouds generating this specific rainfall at this observation station. Obviously, to improve the accuracy of satellite rainfall retrieval, these two problems must be solved simultaneously.

To solve the first problem, a crucial approach is to establish a relationship between multispectral satellite measurements and gauge rain rate reasonably. The instantaneous satellite observation of a certain pixel is correlated with the instantaneous rain rate at the corresponding location when the pixel is scanned by the satellite. Considering the cloud movements, especially the relatively fast movements of convective clouds inducing heavy rainfall, the accumulative rain gauge measurements within a relatively short period always correspond to reliable satellite retrieval. Thus, the rainfall retrieval relationship should be established between the satellite observations and the gauge 10-min rainfall to mitigate the impacts from relatively longer measurement period, which has discussed thoroughly and is well solved in Part I.

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If the satellite images are also obtained every 10 min, the continuous retrieval of rain rate becomes much easier. However, the intervals of current geostationary meteorological satellite observations are generally half an hour [e.g., FengYun-2 (FY-2) of China, Multifunctional Transport Satellite (MTSAT) of Japan]. To make the 10-min rainfall retrieval method continuously applicable to the rainfall estimation of half-hour-interval satellite images and to improve the retrieval accuracy of half-hour rainfall, the method for establishing the 10-min-interval satellite images with half-hour-interval satellite images needs to be considered. On this basis, the continuous retrieval of 10-min rain rate can be carried out, and then, through superposition calculation of three consecutive 10-min rainfall retrievals within half an hour, the total half-hour rainfall will be finally determined. Therefore, the tracking and forecasting of cloud movement using geostationary meteorological satellite images are to be discussed in this paper first.

Continuous efforts on tracking and nowcasting of clouds recently benefit this study via proving useful ideas. In general, these ideas can be categorized into three main methods: timing analysis methods, overlapping methods, and cross-correlation methods. The timing analysis method concretely includes Fourier transform (Arking et al. 1978), the singular value decomposition (SVD) method (K. Liu et al. 2008), the schema matching method (Wolf et al. 1977; Brad and Letia 2002), and others. This method is relatively sensitive to the presence of mixtures of motions, changes in cloud shape, and edge effects (Arking et al. 1978), but their shortcoming is the large calculated amount. The basic principle of the overlapping method is to consider the overlapping between the clouds appearing on two successive images. There are plenty of examples of its application (Arnaud et al. 1992; Dixon and Wiener 1993; Handwerker 2002; Morel and Senesi 2002; Zimmer et al. 2008; Vila et al. 2008). This method requires a small calculated amount, but its premise is that the different cloud clusters must have been distinguished through the spectral information. The third method is the cross-correlation method. In particular, based on the principle that the cross-correlation coefficient of the same cloud is maximum in two consecutive images (Hamill and Nehrkorn 1993), this method can be used well for the estimation of the position and the intensity of the cloud cluster; thus, it is widely used in various tracking algorithms (Lesse et al. 1971; Schmetz et al. 1993; Li 1998; Mecklenburg et al. 2000; Carvalho and Jones 2001; Bolliger et al. 2003; Mecikalski and Bedka 2006; Bellerby 2006; Hsu et al. 2009; Bellerby et al. 2009). Moreover, the cross-correlation method can also be applied to rainfall forecasting (Bellon et al. 1992; Wardah et al. 2008). However, if it is applied directly to rainfall forecasting for 0.5–1 h or longer periods (Brémaud and Pointin 1993; Aspegren et al. 2001; G.-R. Liu et al. 2008), relatively large errors of both retrieval and forecasting become inevitable.

This study explores the development of the cloud-motion current tracking algorithm based on the cross-correlation method. By combing this algorithm with 10-min rain-rate retrieval algorithm, an immediate tracking and continuous accumulation technique (ITCAT) of half-hour rainfall retrieval is proposed. The application of this technique effectively overcomes the problem that coverage duration of the precipitation cloud is difficult to be reliably estimated using the half-hour-interval cloud images, so it improves the accuracy of rainfall retrieval, especially for that of heavy rainfall induced by intense convective clouds. Meanwhile, it also provides a feasible idea for improving the accuracy of rainfall nowcasting. This paper includes six sections. Section 2 introduces the satellite and conventional observation data as well as a pretreatment method. Section 3 introduces the cloud-motion current tracking algorithm established by using the cross-correlation method. Section 4 proposes the ITCAT of half-hour rain rate by satellite images. Section 5 evaluates the rainfall retrieval technique. Section 6 provides a summary and concluding remarks.

2. Data

This study mainly focuses on daytime rainfall. The spectral data adopted in this study come from the Visible and Infrared Spin Scan Radiometer (VISSR) of China’s second-generation geostationary meteorological satellite FY-2C, which has five channels: IR channel 1 (IR1 or IR; 10.3–11.3 μm), IR channel 2 (IR2; 11.5–12.5 μm), water vapor channel (WV; 6.3–7.6 μm), middle IR channel (MIR; 3.5–4.0 μm), and VIS channel (VIS; 0.55–0.90 μm). Except for the VIS channel providing information of albedo, other channels provide brightness temperatures.

The normalization has been carried out on the VIS albedo (same as that in Part I). The equal longitude–latitude projection method is used for all the satellite images. For the projection center, the latitude is 29°42′N, the longitude is 111°12′E, and the spatial resolution is 0.05°. The half-hour-interval satellite images of 90 days from June to August 2008 are used for modeling, analysis, and testing.

The concerned region is the same as that in Part I. The 10-min rain-rate data recorded in the same period with the satellite observation are selected as the rainfall data, which were acquired by more than 300 automatic rain gauges in Anhui, China (with the latitude range of 29°18’–34°52’N and the longitude range of 114°56’–119°37’E). Anhui is located in the time zone of UTC + 8 h, so the time in this study refers to the Beijing time (BT).
3. Cloud-motion current tracking algorithm

The core of the cloud-motion current tracking algorithm is to use the cross-correlation method for obtaining the displacement vectors (movement speed and direction) of cloud clusters on the two consecutive satellite observation images. In a short term, it can be reasonably assumed that the movement speed and direction of cloud clusters are maintained at this level, and the location of cloud clusters at a certain instant can be calculated through interpolation or extrapolation, thus achieving the immediate tracking or nowcasting of cloud-motion currents.

a. Displacement vectors derived by the cross-correlation method

The cross-correlation method deals with two cloud images. First of all, a certain pixel subset $S$ is selected on the satellite image at $t_1$. Then the cross-correlation coefficients between each pixel subset $T_i$ in the corresponding expanded area $A$ on the satellite image at $t_2$ and subset $S$ are calculated, and the pixel subset $T$ with the maximum cross-correlation coefficient is identified. Thus, the vector between the center of pixel subset $S$ and that of pixel subset $T$ can be considered as the displacement of pixel subset $S$ (Fig. 1). The sizes for the subset $S$ and expanded area $A$ in this paper are $15 \times 15$ pixels and $41 \times 41$ pixels, respectively.

FY-2C contains five spectral channels. In theory, a set of displacement vector values can be calculated from the pixel subsets of these channels, but they vary greatly. Therefore, it is necessary to select the appropriate channel to define the displacement vector values of pixel subset. The brightness temperature value of low-altitude cloud top is not easy to be detected with WV channel; the observed MIR radiance is greatly influenced by the solar radiance in the daytime, and the normalization is required for the albedo of VIS channel. Thus, these channels are not ideal for displacement vector calculation. Therefore, the IR channel is ultimately selected to calculate the displacement vector values of pixel subset.

b. Tracking and forecasting of cloud-motion current

In a short term, it is assumed that the motion speed of cloud clusters has little change and then the cloud-motion current can be tracked and forecasted by linear interpolation and extrapolation. The cloud-motion vector field derived from the cross-correlation method is based on each pixel of the image; when motion vectors are applied to interpolation and extrapolation of all pixels of the image, the synthesis action displays cloud cluster motion.

Specific steps are shown in Fig. 2. According to the images at time $t_1$ and $t_2$, the motion vector $V$ of each pixel can be calculated by using the cross-correlation method. The pixels’ radiation value at time $t_2$ is the same as that at the tracking and forecasting time. The pixel at time $t_a$ (interpolation tracking) is to make the pixel at time $t_2$ move backward by $(t_2 - t_a)V/(t_2 - t_1)$; the pixel at time $t_b$ (extrapolation forecasting) is to make the pixel at time $t_2$ move forward by $(t_b - t_2)V/(t_2 - t_1)$. When all the pixels have been moved to the corresponding location, the immediate tracking and nowcasting of cloud-motion current is completed.

Figure 3 shows the cloud image series from 1130 to 1220 BT 23 June 2008 obtained by using this method. In the figure, the cloud images at 1130 and 1220 BT were measured, and then those at 1140 and 1150 BT were obtained through interpolation tracking and those at 1210 and 1220 BT were obtained through extrapolation forecasting. By comparing 1130 and 1200 BT cloud images, it can be seen that a multilayer cloud C existed on the
northeast of cloud image and a cloud band A occurred along the southwest–northeast direction, both of which had large eastward movement speeds. The cumulonimbus cluster B developed in the middle of the cloud image. The eastward moving process of A and C, as well as the development of B, is well reflected in the retrieval and forecast images.

Figure 4 further shows the forecast effects within a longer term. On the left side is the forecast image, and on the right side is the corresponding measured image. It can be seen that the one-hour forecast (Fig. 4c) successfully estimates the location of cloud clusters, but with a little distortion of the intensity estimation. During the time from 1230 to 1300 BT, the strong-cumulonimbus cluster D (i.e., cloud cluster B in Fig. 3) was in the strengthening phase, with the brightness temperature of the intensity center below $-86^\circ C$ and a wide range of anvil clouds obviously appearing on its south; cumulonimbus cluster E in the bottom left of the image weakened in the eastward-moving process with the brightness temperature of intensity center being $-60^\circ C$; and the cloud cluster F at the sea was seriously filamentary. On the forecast image, the cloud cluster D does not develop vigorously, with the brightness temperature of intensity center being $-78^\circ C$, and no anvil-cirrus clouds appear to the south of them; the cloud cluster E still has the brightness temperature of intensity center as $-70^\circ C$ with the intensity greater than that of measured image; and the cloud cluster F still has clear structures, with the filamentary phenomenon less obvious than that of the measured image.

It can be seen that the cloud-motion current tracking algorithm can accurately track and forecast the movement of cloud clusters. Especially for the cloud clusters with slow shape changes and relatively smooth movement, the accurate positioning can be achieved with this algorithm. However, because only the cloud cluster movement is considered without taking brightness temperature changes into account in the cloud-motion current tracking algorithm, the tracking and forecasting of developing or dispersing cloud intensity are not very satisfactory. This defect is shown more obviously in the longer-term forecast of summer convective clouds. However, for half-hour nowcasting of cloud clusters, this algorithm will be completely feasible because of slight changes in the intensity of cloud clusters.

All of the above discussions are concentrated on clouds on the IR channel. For the clouds of other channels, the displacement vectors obtained through the IR channel are also used for retrieval and forecasting (images omitted) so as to maintain consistency with the spectral information of cloud images.

4. Retrieval and nowcasting of half-hour rainfall

Combining the 10-min rainfall retrieval algorithm discussed in Part I with the cloud-motion current tracking algorithm based on the cross-correlation method mentioned in section 3, the satellite retrieval and forecasting technique of half-hour rainfall is established accordingly: that is, ITCAT of half-hour rainfall retrieval.

a. Principle of half-hour rainfall retrieval

The observation is conducted by FY-2C satellite every half an hour, whereas the rainfall estimation method discussed in Part I only involves the 10-min rainfall. Therefore, the establishment of 10-min-interval satellite image sequences is required to accomplish the continuous rainfall retrieval. Based on the two consecutive measured images within half an hour, the displacement vector derived from the cross-correlation method can be used for the calculation of interpolation images in the specified intervals (10 and 20 min). For example, the images at 1110 and 1120 BT are interpolated using those at 1100 and 1130 BT. Then, the corresponding 10-min rainfall can be retrieved with the image at the initial time (i.e., the first measured image) and the two interpolated 10-min-interval images (a total of three images), respectively. Finally, the half-hour rainfall is retrieved with an accumulative superposition for every pixel.
b. Principle of half-hour rainfall nowcasting

The nowcasting technique of half-hour rainfall is similar to the retrieval technique, but the difference lies in that the satellite image sequences are obtained through extrapolation (e.g., the images at 1140 and 1150 BT can be extrapolated using those at 1100 and 1130 BT). Then, the subsequent half-hour rainfall is forecasted using the measured image at the terminal time (i.e., the second measured image) and the two extrapolated images (a total of three images). In theory, the image at any time can be obtained through the extrapolation of two satellite images. However, as has been mentioned in the previous section, significant defects exist in the forecast of the scope and intensity of cloud clusters beyond a half-hour. Therefore, the extrapolation discussed in this paper only performs on half-hour rainfall.

c. Process summary

In general, the process of half-hour rainfall retrieval and nowcasting technique can be illustrated in Fig. 5. The consecutive images of every 10 min (a total of six images including two measured images) can be obtained through performing interpolation or extrapolation on the two images at the time of \( T \) and \( T + 30 \) min (measured images). With the sequential application of RPIM for rainfall area division and the MSCFRA for rainfall rate estimation, the six images can be used to obtain the 10-min rainfall distribution maps. Through the accumulation of the rainfall on rainfall distribution maps estimated using images at the times \( T \), \( T + 10 \) min, and \( T + 20 \) min, the real-time monitoring map of half-hour rainfall can be obtained. Moreover, through the accumulation of the rainfall on rainfall distribution maps estimated using
images at the times $T + 30\text{ min}$, $T + 30\text{ min}$, and $T + 40\text{ min}$, the nowcasting map of half-hour rainfall can be obtained. The entire process proves that real-time monitoring and nowcasting process of half-hour rainfall field can be accomplished simultaneously.

5. Evaluation on the rainfall retrieval technique

In this study, the comparison and evaluation on the rainfall retrieval technique, adopt the conventional statistical indicators used in the previous relevant studies (Ba and Gruber 2001; Kuligowski 2002; Yan and Yang 2007), such as root-mean-square deviation (rmsd) and correlation coefficient (cc), which are defined as follows:

\[
\text{rmsd} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (S_i - G_i)^2}\ 
\text{and,}\ 
\]

\[
\text{cc} = \frac{\sum_{i=1}^{N} (S_i - \bar{S})(G_i - \bar{G})}{\sqrt{\sum_{i=1}^{N} (S_i - \bar{S})^2} \sqrt{\sum_{i=1}^{N} (G_i - \bar{G})^2}}. 
\]

where

\[
\bar{G} = \frac{\sum_{i=1}^{N} G_i}{N};
\]

\[
\bar{S} = \frac{\sum_{i=1}^{N} S_i}{N};
\]

and $S_i$ and $G_i$ are satellite estimated rain rate and rain gauge–measured rain rate, respectively.

Taking into account the characteristics of instantaneous satellite observations and potential cloud nonlinear movement in 10 min, in the accuracy test of the satellite retrieval rain rate under the pixel resolution, the comparison between point-to-point values (the rain rate of each individual rain gauge station to that of satellite retrieval at that station) is less suitable. Therefore, the comparison between a point (the rain rate of each individual rain gauge station) and an area [retrieval rainfall area with that station as the center and a radius of the “comparison radius (Rc)”] is conducted here. The satellite retrieval

![Figure 4. Half-hour and one-hour forecast images and the comparison with the measured images. The four images are half-hour (a) forecast (1230 BT) image and (b) measured image and one-hour (c) forecast (1300 BT) image and (d) measured image. Figures 3a,d are the analysis images used.](image-url)
rain rate most approximating to rain gauge rain rate within the area is taken to represent the estimate at that station. $R_c$ is determined by the cloud movement speed. Obviously, different values of $R_c$ will lead to significantly different statistical results. To ensure the objective evaluation of the retrieval accuracy, $R_c$ is set as 1, 3, and 5 satellite pixels in this study to evaluate the algorithms of half-hour rainfall retrieval and nowcasting.

**a. Evaluation on half-hour rainfall retrieval**

Four representative precipitation processes occurring on 10 June, 21 June, 1 August, and 15 August 2008 are selected for the evaluation. Anhui Province is located at the critical region under the mei-yu front effect, and its precipitation type is mainly the mixed precipitation, which combines the characteristics of nimbostratus and cumulonimbus precipitation. However, for each specific precipitation process, only one type of precipitation is dominant.

For example, on 10 June, all areas in Anhui were mainly controlled by nimbostratus, which was expressed as continuous precipitation. Because the movement and intensity variations of stratiform clouds are very slow, the difficulty of retrieval is to determine when the rain begins and how much the rain rate will be in the areas under the border of the nimbostratus. The rain rate of nimbostratus is relatively small, and the rain rate of its border is even smaller [only about 0.5 mm ($0.5 \text{ h}^{-1}$)], which explains its overestimate in the previous rainfall algorithms. This half-hour rainfall retrieval method has a good effect on the rainfall

**FIG. 5. Flowchart of the ITCAT for half-hour rainfall retrieval.** The square represents the satellite images; the diamond represents the 10-min rainfall distribution map; and the hexagon represents the half-hour accumulative rainfall distribution map. The rectangular filled in blue with a solid frame represents the cloud-motion current tracking algorithm, and the rectangular filled in yellow with a solid frame represents the 10-min rainfall retrieval algorithm using single image.
estimation of nimbostratus. It can be seen from Table 1 that, even though the Rc is 1 pixel, the cc between the estimated value and the rain gauge measurement reaches as high as 0.72. It indicates that this algorithm could determine the location and intensity of rainfall accurately. If Rc is enlarged to 3 pixels, then, cc will exceed 0.84 and rmsd will become significantly smaller. With the increase of Rc, the increase of the cc becomes slower and rmsd also gets smaller at a slow speed. When Rc is 5 pixels, cc reaches 0.9.

The other three precipitations (21 June, 1 August, and 15 August) mainly manifest as deep convective precipitation. The convective clouds are characterized by a fast movement speed, drastic intensity variation, and complex rainfall distribution. Consequently, the accuracy of the convective precipitation retrieval is poorer than the stratiform precipitation one. In Table 1, when Rc is 1 pixel, the cc between the estimated value and the rain gauge–measured value is slightly over 0.5. Although this cc can be considered relatively high and had passed the significance test with the confidence degree of 95%, the retrieval effect of the convective precipitation is significantly poorer than that of stratiform precipitation; rmsd value is also great, even 2 times greater than the average. Such statistical results indicate that rainfalls of many observation stations are not correctly estimated. If the comparison area near the observation station is expanded with Rc set as 3 pixels, the cc will be rapidly elevated over 0.75, which may even exceed that of nimbostratus retrieval (e.g., on 21 June), and the cc will also decrease a great deal. The improvement will become even more obvious when Rc is set as 5 pixels. It is implied that, because the movement of cumulonimbus clouds is not linear movement with constant velocity, the tracking of cumulonimbus-motion current with the cross-correlation method may give rise to the error of 3–5 pixels in the positioning of cumulonimbus clouds with rapid movement. Moreover, the rapid variation in the intensity and coverage area of cumulonimbus clouds is also an important influencing factor. It can be seen that the half-hour rainfall retrieval technique leaves much room for improvement. If the time resolution of satellite observations can be improved to be 10 min or shorter, a more effective improvement of the accuracy and quality of satellite rainfall retrieval can be expected.

Figure 6 shows the scatter diagram of rain gauge rain rate and satellite retrieval rainfall estimation under different Rc values in the four examples listed in Table 1. When Rc is 1 pixel (i.e., when the spectral images of satellite observations and ground observation stations are basically matched in a point-to-point manner), the retrieval algorithm for the half-hour cumuliform rainfall tends to overestimate the weak rainfall [<2.5 mm (0.5 h)⁻¹], whereas, for the stratiform rainfall, the strong rainfall [≥15 mm (0.5 h)⁻¹] is likely to be underestimated. If the nonlinear cloud movement is taken into account and Rc is set as 3 or 5 pixels, whether for stratiform clouds or cumulus clouds, the estimated values and the observed values of the rainfall are basically consistent. However, the rainfall of individual observation stations is still obviously underestimated in some cases. The underestimation cannot be wholly attributed to the defect of retrieval technique, because it may also result from the observation errors of the automatic stations or the inconsistency between resolutions of satellite observation and ground-based stations (Ba and Gruber 2001; Wei et al. 2006).

Figure 7 shows the nimbostratus precipitation process in Anhui around 1200 BT 10 June 2008, and the FY-2C IR and VIS channel data at relevant time are used for a continuous tracking retrieval test of the precipitation cloud. In general, the distribution of different rain-rate grades in the rainfall area is well identified by the half-hour rainfall retrieval technique, the intensity center is estimated quite accurately, and the ground-measured rainfall grade and satellite retrieval rainfall grade are basically consistent. However, it should be noted that, on the retrieval map, the rainfalls of 2.6–8.0 mm (0.5 h)⁻¹ at several rain gauges north of Yangtze River at the western region of Anhui Province are underestimated. Moreover, the rain rates of several isolated individual rain gauges in southern Anhui exceed 16.0 mm (0.5 h)⁻¹ during the period from 1230 to 1300 BT, but no strong-cumulonimbus spectrum
Fig. 6. The scatter diagram of rain gauge rain rate (denoted as Gauge) and satellite retrieval rainfall estimation (denoted as Estimated) under different Rc (units in pixels). The daily statistical time is 900–1600 BT, and the statistical data are collected every half hour.
characteristics are displayed on the images. Therefore, the rainfalls are estimated to be the light rain of 0.5–2.5 mm \(0.5\ h^{-1}\). These errors may be resulted from the strong rainfall induced by convective clouds of warm cloud top, but they are more likely to be caused by the low resolution of satellite observations. The spatial resolution of FY-2C is 5 km, and, if the area represented by the pixel is not completely covered by newly generated strong convection cells, the radiation of this pixel will be significantly affected by the lower-level radiation outside the cloud, which will result in the wrong judgment of rain-rate retrieval.

b. Accuracy comparison with the previous algorithm

In the previous satellite rainfall retrieval algorithms, a single satellite image was generally used in the retrieval of half an hour, an hour, or an even longer

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**Fig. 7.** The effect map of half-hour rainfall retrieval (10 Jun 2008). The rain rate is divided into six grades: that is, grade 0 \([0 \ mm \ (0.5 \ h)^{-1}\), grade 1 \([<0.5 \ mm \ (0.5 \ h)^{-1}\), grade 2 \([0.5–2.5 \ mm \ (0.5 \ h)^{-1}\), grade 3 \([2.6–8.0 \ mm \ (0.5 \ h)^{-1}\), grade 4 \([8.1–15.9 \ mm \ (0.5 \ h)^{-1}\), and grade 5 \([>16.0 \ mm \ (0.5 \ h)^{-1}\). The corresponding times are (a) 1100–1130 BT, (b) 1130–1200 BT, (c) 1200–1230 BT, and (d) 1230–1300 BT in sequence. The no-rainfall area is denoted with the gray level of the IR brightness temperature on the first image; the dots represent the measured rain rate, and the different colors corresponding to the color scale indicate the different rainfall grades.
period of rainfall (Wei et al. 2006; Yan and Yang 2007; Gourley et al. 2010). Obviously, the ITCAT of rainfall retrieval is more reasonable than these algorithms. Examples and statistical results also testify that the former can significantly improve the accuracy of rainfall retrieval than the latter.

First, the case matching satellite data with ground-based in situ rainfall of two stations (Table 2) is used for a simple illustration. Station 1 was located at the intensity center of the cloud cluster in the first 10 min. The cloud cluster resulted in very heavy rainfall, and the rain rate significantly decreased as the cloud cluster gradually left the station. This process can be revealed step by step with the adoption of the cross-correlation method in tracking cloud clusters, and all of the 10-min rainfall retrievals are consistent with the actual rainfall of the observation stations. If only the single satellite image is used directly for rainfall retrieval, the subsequent half-hour rainfall will be overestimated because of the low brightness temperature and high albedo.

Table 2. The corresponding spectral characteristics and rain rate of stations 1 and 2, including the infrared brightness temperature $T_b$, visible albedo $A$, rain gauge–measured rain rate $G$, and satellite-estimated rain rate $S$. The national standard station number of station 1 is 14355 (located at 32.218°N, 116.5547°E). The national standard station number of station 2 is 17352 (located at 30.3556°N, 117.4376°E).

<table>
<thead>
<tr>
<th>Time</th>
<th>Station 1</th>
<th>Station 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>First 10 min</td>
<td>Second 10 min</td>
</tr>
<tr>
<td>1030–1100 BT 21 June 2008: Station 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_b$ (K)</td>
<td>205.35</td>
<td>208.45</td>
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<tr>
<td>$A$</td>
<td>0.67</td>
<td>0.67</td>
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<tr>
<td>$G$ [mm (10 min)$^{-1}$]</td>
<td>8.8</td>
<td>5</td>
</tr>
<tr>
<td>$S$ [mm (10 min)$^{-1}$]</td>
<td>7.7</td>
<td>6</td>
</tr>
<tr>
<td>1400–1430 BT 2 Jul 2008: Station 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_b$ (K)</td>
<td>225.28</td>
<td>221.06</td>
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<tr>
<td>$A$</td>
<td>0.58</td>
<td>0.65</td>
</tr>
<tr>
<td>$G$ [mm (10 min)$^{-1}$]</td>
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<td>4</td>
</tr>
<tr>
<td>$S$ [mm (10 min)$^{-1}$]</td>
<td>0</td>
<td>1.9</td>
</tr>
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</table>

FIG. 8. The estimation status of each rainfall grade using (left) the previous algorithm and (right) the current algorithm. The four histograms of each grade are corresponding to the rainfall processes on 10 Jun, 21 Jun, 1 Aug, and 15 Aug 2008. The division method for operational forecasts is adopted in the division of rainfall grades: that is, slight rain ($<$0.5 mm h$^{-1}$), light rain (0.5–2.5 mm h$^{-1}$), moderate rain (2.6–8 mm h$^{-1}$), heavy rain (8.1–15.9 mm h$^{-1}$), and rainstorm ($\geq$16.0 mm h$^{-1}$).
The process of station 2 is just the contrary to that of station 1. The cloud cluster had not yet moved to station 2 within the first 10 min. Thus, the spectral characteristics were shown as high brightness temperature and low albedo, and a low rain rate was expected to occur in the retrieval (identical with the measured result). The intensity center of the cloud cluster covered station 2 in the third 10 min, and, only at this time, relatively heavy rainfall was observed at station 2. If only the single satellite cloud image is used for half-hour rainfall retrieval, the rain rate of station 2 will be significantly underestimated because of the weak spectral characteristics of radiation. With the adoption of the cross-correlation method to track cloud clusters, three 10-min rainfalls are retrieved. Then, the process in which cloud cluster moved and gradually covered station 2 can be well revealed.

Therefore, the cloud-motion current tracking algorithm is used to track moving cloud clusters (especially cumuliform clouds), and the rainfall is retrieved accordingly. Each 10-min period rain rate well corresponds to the spectral information, and the accumulated 30-min rain rate also has a high accuracy.

To further verify the accuracy and reliability in the ITCAT of rainfall retrieval proposed in this study (referred to here as the previous algorithm), the case comparison in continuous rainfall retrieval is carried out on four typical precipitation processes between the current algorithm and the algorithm in which the single satellite image is used for one-hour rainfall retrieval (referred to here as the previous algorithm; Zhuge and Yu 2009).

<table>
<thead>
<tr>
<th>Date</th>
<th>No. of samples</th>
<th>10 June 2008</th>
<th>1 Aug 2008</th>
<th>15 Aug 2008</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>cc 0.47</td>
<td>1.68</td>
<td>1.84</td>
<td>2.16</td>
</tr>
<tr>
<td></td>
<td>rmsd [mm (0.5 h)⁻¹]</td>
<td>2.03</td>
<td>3.70</td>
<td>7.42</td>
</tr>
<tr>
<td></td>
<td>$\overline{\gamma}$ [mm (0.5 h)⁻¹]</td>
<td>1.68</td>
<td>1.84</td>
<td>2.16</td>
</tr>
<tr>
<td></td>
<td>$\overline{\delta}$ [mm (0.5 h)⁻¹]</td>
<td>1.82</td>
<td>3.24</td>
<td>4.83</td>
</tr>
<tr>
<td></td>
<td>cc 0.47</td>
<td>2.03</td>
<td>3.70</td>
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<td>rmsd [mm (0.5 h)⁻¹]</td>
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<td>2.03</td>
<td>3.70</td>
<td>7.42</td>
</tr>
</tbody>
</table>

Rc is set as 5 pixels, and various estimations of rainfall are compared for each rainfall grade. Accurate assessment occurs when estimated rainfall grade and rain gauge–measured rainfall grade are consistent. The division method of operational forecast is adopted in the division of rainfall grade; that is, there are five grades: namely, slight rain (0.0–0.5 mm h⁻¹), light rain (0.5–2.5 mm h⁻¹), moderate rain (2.6–8 mm h⁻¹), heavy rain (8.1–15.9 mm h⁻¹), and rainstorm (≥16.0 mm h⁻¹). The comparison results are shown in Fig. 8, where four histograms exist in each grade, corresponding to four precipitation processes on 10 June, 21 June, 1 August, and 15 August 2008, respectively.

It can be seen that the previous algorithm has the advantage in the grade estimation of light rain and moderate rain, with the correct rate being basically over 84.9% (except the estimation of moderate rain on 10 June). The correct rate of grade estimation for light rain on 10 June even reaches 97.8%. However, the greatest defect of the previous algorithm is that a relatively great error exists in the grade estimation of slight rain and heavy rain. The slight rain of <0.5 mm h⁻¹ is easy to be underestimated as no rain, and the percentage of underestimation even exceeds 90% (10 June, 21 June, and 15 August). Moreover, slight rain that is not underestimated is mostly overestimated. The previous algorithm is also easy to underestimate heavy rainfall (heavy rain and rainstorm), which is rather obvious in the rainstorm estimation on 10 June, with the underestimation rate reaching 87.1%, and the underestimation rate of rainstorm in other processes is also relatively large. Through the comparison of rainfall results in four processes, it is concluded that the estimation of stratiform rainfall with the previous algorithm is poorer than that of the cumuliform cloud rainfall, because the estimations of stratiform slight rain and rainstorm almost completely fail.

The current algorithm is relatively successful in improving results. For the grade estimation of slight rain, the underestimation rate is reduced below 45% and the correct rate is significantly elevated. Except on 1 August, the correct rates of other processes are all larger than the underestimation rates. Especially on 10 June, the correct rate of slight rain estimation reaches 65.8%. The correct estimation rates of rainstorm all exceed 85%. The advantage of the previous algorithm is maintained in the estimation of light rain and moderate rain. Compared with the previous algorithm, the rainfall estimation with the current algorithm is significantly improved both for stratiform clouds and cumuliform clouds. As viewed from the results, the estimations of the two types of rainfall with the current algorithm are relatively satisfactory.
Fig. 9. As in Fig. 6, but for the rainfall forecast.
c. Evaluation on half-hour rainfall nowcasting

The half-hour rainfall nowcasting is also evaluated. The statistical data are shown in Table 3, and the corresponding scatter diagram is shown in Fig. 9. By comparing Tables 1 and 3 and Figs. 6 and 9, it can be seen that the effect of the half-hour rainfall nowcasting is close to that of half-hour rainfall retrieval (slightly poorer than the retrieval). Therefore, the algorithm of half-hour rainfall nowcasting in this study is successful. The major reason is that the movement of precipitation clouds is accurately estimated, and the duration and intensity change of rainfall at the observation stations are also reliably tracked. In addition, the rainfall nowcasting method presented in this study does not depend on rain gauge. Thus, it has wide applicability and can be used for operational forecasting tests.

However, it must be pointed out that the constraint conditions of the ITCAT shall be paid attention to during its application. It is assumed that the displacement vector and the radiation values (brightness temperature or albedo) of each pixel during the moving process remain unchanged in a short time, which results in the estimated rain rate of this pixel remaining unchanged. This error will be tolerated within a relatively short period (e.g., half an hour), but, with an increase in the extrapolation time, the error might be significantly greater, especially for the intense convective cloud at the primary and development stage, which is also proven by the comparison results of several cases above. To fundamentally solve this problem, it is necessary to improve the time resolution of satellite observations.

6. Conclusions

Based on the study in Part I, the immediate tracking and continuous accumulation technique (ITCAT) of half-hour rainfall retrieval is proposed by further integrating the cross-correlation method. ITCAT includes two steps. 1) The cross-correlation method is applied to track cloud-motion currents and establish 10-min-interval image sequences. 2) A continuous retrieval of 10-min rain rates is conducted with the image sequences, and finally a total half-hour rainfall is determined by accumulations. The accuracy of rainfall retrieval is significantly increased in both rainfall monitoring and nowcasting. If the half-hour-interval image is applied directly to estimate rainfall, errors in estimation will often result from the unreliable estimation of the coverage duration of rainfall cloud.

ITCAT is the organic combination of cross-correlation method and the retrieval method of the 10-min rain rate, which provides a new feasible idea for improving rainfall monitoring and nowcasting accuracy. Because of the considerations of the movement process of cloud clusters, rainfall retrieval can estimate the coverage duration of rainfall clouds over the observation station and their intensity changes dynamically, thus improving the reliability of rainfall intensity retrieval significantly. The continuous forecast tests of half-hour rainfall field also prove that this idea is of positive significance to improve rainfall nowcasting, especially nowcasting of intense convective precipitation. It also shows that, if the time resolution of satellite observations can be elevated to be 10 min or even shorter, further effective improvement of the accuracy and quality of satellite rainfall retrieval can be expected.

ITCAT provides satisfactory results in the retrieval and nowcasting of rainfall intensity. However, it should be noted that constant intensity and speed of cloud clusters are assumed in the cloud-motion current tracking algorithm. Therefore, ITCAT can only be applied for a half-hour-interval nowcasting of rainfall intensity at present. It is necessary to further improve the forecast technology of cloud cluster intensity within a longer term. In addition, the retrieval and forecasting of rainfall intensity with the combined adoption of IR brightness temperature and VIS albedo can only be applied in the daytime. MIR, WV, and other channel information are required to achieve all-day rainfall retrieval and nowcasting (mainly for nighttime rainfall). In the subsequent studies, these two aspects will be focused on.

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REFERENCES


