Research Article

Automatic Tracking and Characterization of Cumulonimbus Clouds from FY-2C Geostationary Meteorological Satellite Images

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This paper presents an automated method to track cumulonimbus (Cb) clouds based on cloud classification and characterizes Cb behavior from FengYun-2C (FY-2C). First, a seeded region growing (SRG) algorithm is used with artificial neural network (ANN) cloud classification as preprocessing to identify consistent homogeneous Cb patches from infrared images. Second, a cross-correlation-based approach is used to track Cb patches within an image sequence. Third, 7 pixel parameters and 19 cloud patch parameters of Cb are derived. To assess the performance of the proposed method, 8 cases exhibiting different life stages and the temporal evolution of a single case are analyzed. The results show that (1) the proposed method is capable of locating and tracking Cb until dissipation and can account for the eventual splitting or merging of clouds; (2) compared to traditional brightness temperature (TB) thresholds-based cloud tracking methods, the proposed method reduces the uncertainty stemming from TB thresholds by classifying clouds with multichannel data in an advanced manner; and (3) the configuration and developmental stages of Cb that the method identifies are close to reality, suggesting that the characterization of Cb can provide detailed insight into the study of the motion and development of thunderstorms.

1. Introduction

In the tropics and midlatitudes, cumulonimbus (Cb) clouds are associated with intense convection and severe weather such as wind gusts, heavy precipitation, lightning, and eventually hail, microbursts, and tornadoes. Their presence may pose a serious risk to aviation and may impact crops and urban populations because rapidly changing weather on various spatial and temporal scales may occur within and near Cb clouds. Observations of Cb can be an important source of data for assimilation in weather forecasting and for monitoring climate trends [1].

Geostationary satellite images have been proven to be an important source of observations of dynamic weather events. They are especially useful for convective cloud tracking, thanks to their high temporal resolution and large field of view compared to that of Doppler radars and atmospheric profilers [2, 3]. The determination of characteristics of Cb based on cloud tracking from geostationary imageries may improve existing precipitation estimation and nowcasting schemes.

The identification and monitoring of cloud began with manual tracking, such as the work of Martin and Schreiner [4], Rowell and Milford [5], and Fritsch and colleagues

[6–9]. Those studies are labor intensive and somewhat subjective despite the great improvement in the understanding of the diurnal phases of large convective cloud systems (CS). With the development of faster computers and the introduction of image-processing methods, families of automatic tracking techniques were used, such as the procedure based on a propagation speed criterion by Woodley et al. [10], the algorithm to locate winter monsoon cloud clusters by Williams and Houze [11], the automatic method of tracking clouds with cold tops in African convective systems by Arnaud et al. [12], the algorithm to monitor mesoscale convective systems (MCSs) in Greece by Feidas and Cartalis [13], the Maximum Spatial Correlation Tracking Technique (MASCOTTE) by Carvalho and Jones [14], the Cloud-Top Cooling Rate (CTC) algorithm by the University of Wisconsin [15], and Rapid Developing Thunderstorm (RDT) by Météo-France [16]. Almost all these cloud tracking methods employ the infrared (IR) brightness temperature (TB) threshold principle [17]. However, for Cb detection, determination of the TB threshold in satellite scenes is a difficult task complicated by spatially and temporally varying surface reflectivity of underlying land surface, complex multilayer cloud structures, and highly variable water vapor content. Thus, neither static thresholds nor climatologically based thresholds are likely to produce robust Cb detection in any given scene. The problem often is further complicated by sensor-related issues due to multiple layers of cloud moving at different speeds and in different directions.

Up to now, there are numerous literatures documented on severe storms characters [18, 19], such as the variation of shooting tops [20–23], the diagnosis/nowcast of convective initiation (CI) [24–28], the formation of MCSs and mesoscale convective complexes (MCCs) [13, 14, 29–31], cloud microphysical processes [32], and the variation of intense convection [33–38]. And a lot of papers have been written concerning characteristics of Cb, such as the dynamical variation of Cb [38, 39] and predictability of evolution [40]. Yet, they are mainly based on cloud numerical models and much less on satellite data. The dedicated study to track Cb from geostationary imagery is Cumulonimbus Tracking and Monitoring (Cb-TRAM) by Zinner et al. [41], which uses a pyramidal image matcher and a convective cloud mask from ECMWF tropopause temperature data as an adaptive detection criterion. The Cb detection is essentially based on a climatological threshold principle. Therefore, a more comprehensive multichannel method of cloud classification may help to identify the temporal evolution and spatial properties of convective clouds that cannot be properly investigated with single channel threshold techniques.

A number of cloud classification methods have been developed for remote-sensing instruments using various techniques, such as neural networks [42], clustering analysis [43], maximum likelihood analysis [44], and fuzzy logic [45]. According to previous studies, a neural network classifier usually performs well if it is well trained [46]. In this study, a neural network classifier is used to cluster cloud pixels with similar spectral properties based on three infrared (IR) channels (IR1, 10.3–11.3 μm ; IR2, 11.5–12.5 μm ; and WV, 6.3–7.6 μm) of FengYun-2C (FY-2C), which is the

first operational Chinese-based geostationary meteorological satellite. The spatial resolution of FY-2C is 5 km at the satellite nadir point, and it collects imageries hourly in normal state time and half hourly in rainy seasons. FY-2C was launched successfully from Beijing on October 19, 2004.

At present, the satellite-based analysis of cloud usually uses Geostationary Operational Environmental Satellite (GOES) instruments (GOES-9-12 in particular), Advanced Very High Resolution Radiometer (AVHRR), Meteosat, and METEOSAT Second Generation (MSG). Studies from FengYun (FY) satellites are seldom found despite the fact that four operational geostationary meteorological satellites had been developed by China. Tracking and characterizing Cb from FY satellites may give new insight into the understanding of precipitation system of East Asia.

The main contribution of this paper can be summarized as follows: (1) presenting an automatic Cb tracking method based on the identification of Cb from cloud classification; (2) characterizing Cb systematically from geostationary satellite both from pixel and from cloud patch levels; and (3) improving the ability to track and investigate properties of Cb in East Asia using FY-2C and preparing cloud analysis and monitoring method for the upcoming launches of the FY-4 satellite series.

The structure of this paper is as follows. The proposed Cb detection and tracking method is presented in Section 2. Features of Cb identified by this method are introduced in Section 3. To illustrate the performance of this technique, specific cases are analyzed in Section 4. The conclusions and discussion are given in Section 5.

2. Methodology for Cb Tracking

The objective of Cb tracking is to identify Cb from satellite imageries and to track their evolution on an image-by-image basis over time. In this work, the proposed technique of Cb tracking consists of three steps: the identification of Cb pixels using an artificial neural network (ANN) classifier [46], the detection of homogeneous Cb patches with a seeded region growing (SRG) algorithm, and the establishment of a relationship between current and previous Cb patches using a cross-correlation-based approach.

2.1. Cloud Classification. The purpose of this step is to extract various clouds from multichannel imageries using cloud classifiers.

Considering an ANN classifier as a biologically inspired computer program designed to simulate the way in which the human brain processes information, it is a promising modeling technique, especially for data sets having nonlinear relationships, which are frequently encountered in cloud classification processes. This study used an ANN cloud classification method for FY-2C data, which has been developed by comparing the capabilities of six widely used ANN methods (back

FIGURE 1: Configuration for cloud classification and segmentation of cumulonimbus (Cb). The cloud classification used artificial neural network (ANN) method, and segmentation used seeded region growing (SRG) method; CT_{seed} : cloud type of seed; $CT_{(x,y)}$: cloud type of pixel (x, y) . TB_1, TB_2 , and TB_3 are the brightness temperature (TB) of three infrared (IR) channels (IR1, 10.3–11.3 μm ; IR2, 11.5–12.5 μm ; and WV 6.3–7.6 μm), respectively; G_1, G_2 , and G_3 are the gray value for three infrared (IR) channels, respectively.

propagation (BP), probabilistic neural network (PNN), modular neural networks (MNN), Jordan-Elman network, self-organizing map (SOM), coactive neurofuzzy inference system (CANFIS), and two other methods (principal component analysis (PCA) and a support vector machine (SVM)). The scheme of the ANN cloud classification is shown in Figure 1. In this study, the ANN classifier divided cloud/surface into seven categories: sea, stratocumulus and altocumulus, mixed cloud, altostratus and nimbostratus, cirrostratus, thick cirrus, and cumulonimbus using 2864 cloud

samples manually collected by two experienced meteorologists in June, July, and August in 2007 from three FY-2C channels' (IR1, 10.3–11.3 μm ; IR2, 11.5–12.5 μm ; and WV 6.3–7.6 μm) imagery. And 15 features were chosen with numerous tests: 3 gray features (G_1, G_2 , and G_3), 3 spectral features (TB_1, TB_2 , and TB_3), and 9 assemblage features ($G_1-G_2, G_1-G_3, G_2-G_3, TB_1-TB_2, TB_1-TB_3, TB_2-TB_3, (G_1-G_2)/G_1, (G_1-G_3)/G_1$, and $(G_2-G_3)/G_2$). The ANN classifier was composed of 2 hidden layers, and the neurons of the first and the second layer are 9 and 4, respectively. The learning step

TABLE 1: Confusion matrix of the cloud classification using ANN classifier [46].

Classes	Sea*	Land	Low-level clouds	Midlevel clouds	Thin cirrus	Thick cirrus	Multilayer clouds	Cb
Sea**	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Land	0.00	0.97	0.00	0.01	0.01	0.01	0.00	0.00
Low-level clouds	0.04	0.05	87.00	0.02	0.02	0.00	0.00	0.00
Midlevel clouds	0.01	0.00	0.02	0.92	0.05	0.00	0.00	0.00
Thin cirrus	0.01	0.01	0.02	0.01	0.93	0.02	0.00	0.00
Thick cirrus	0.00	0.00	0.00	0.01	0.02	0.92	0.05	0.00
Multilayer clouds	0.00	0.00	0.00	0.03	0.00	0.01	0.90	0.06
Cb	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.98

* Observed by experience; ** classified by ANN.

and the learning momentums were set as 0.1 and 0.7, and TanhAxon was used as a transfer function. More details concerning the classification method can be found in Liu et al. [46].

The accuracy results were shown in confusion matrix using 274 testing samples (Table 1). It can be seen that the cloud classifier can differentiate Cb well, and the possibility of misjudging other types of clouds as Cb was low with error rate below 6% [46].

This step reduces hundreds of pieces of satellite image data in float format to several pieces of cloud-type data in integer format. Each integer represents a special desired type of cloud patch ($CT_{desired}$).

2.2. Cloud Segmentation. The purpose of this step is to extract cloud boundaries and segment Cb patches using a seeded region growing (SRG) segmentation algorithm based on the result of previous ANN cloud classification. The ANN cloud classification can be thought of as a preprocessing procedure. SRG is an iterative process by which regions are merged starting from some initial segmentation—in this case, individual pixels—and then growing iteratively until every pixel has been processed. The scheme of the SRG segmentation is shown in Figure 1. It contains the following steps: (1) scan the image and identify Cb pixel that has not been labeled as a seed; (2) merge adjacent cloud cells to form a fragment if they are the same type as the seed and label each fragment as a completed region; (3) select unlabeled parts and reapply steps (1) and (2) until the entire image has been labeled.

As shown in Figure 1, unlike the traditional SRG method, this method is not sensitive to the rules for seed selection and growth. The reason is twofold: first, ANN cloud classifiers can reduce the number of infrared image values from hundreds of floats to several integers, where each integer represents a particular type of cloud; second, clouds identified by ANN always have a smoother boundary for the combination of multiple channels than do clouds identified with the traditional threshold methods.

2.3. Cb Tracking. The purposes of this step are to track Cb patches, to detect the different development stages of Cb, and to provide an image sequence with indexed clouds. In general, the tracking method to detect cell patterns, whether

radar- or satellite-data-based, can be divided into two main techniques: pattern-oriented correlation techniques and overlapping techniques [47]. This paper employs the former technique as well as the most common technique, a cross-correlation-based approach that uses two successive IR images to determine a displacement vector. In the first picture, digital image data of 3×3 pixels centered on the desired site are used as template data. In the second picture, taken one hour previously, image data of 15×15 pixels are used as search area data. The correlation coefficient of TB for the template area and the search area is calculated for each point to obtain a cross-correlation coefficient matrix, called a matching surface. The largest coefficient is adopted as the best-matched position at the pixel level, and the cloud advection was extracted. At the cloud patch level, if matched pixels make up more than 50% of the area of either the current cloud patch or the cloud patch from the previous time step, thus the patches are matched. Then, a cloud patch history log file is created to store tracking information and monitoring results.

The performance of the cloud tracking was evaluated with probability of detection (POD), false-alarm ratio (FAR), and critical success index (CSI). They are defined as follows:

$$\begin{aligned}
 \text{POD} &= \frac{\text{hits}}{\text{hits} + \text{misses}}, \\
 \text{FAR} &= \frac{\text{falsealarms}}{\text{hits} + \text{falsealarms}}, \\
 \text{CSI} &= \frac{\text{hits}}{\text{hits} + \text{misses} + \text{falsealarms}},
 \end{aligned} \tag{1}$$

where hits, misses, and false alarms are the number of hits, failures, and false alarms of Cb pixels between the observed and the extrapolated imagery, respectively. The best tracking algorithm should be $\text{POD} = 1$, $\text{FAR} = 0$, and $\text{CSI} = 1$.

3. Characterization of Cb

In this study, Cb characteristics are derived at the pixel and patch levels, as shown in Table 2. Three types of cloud pixel parameters are extracted: coldness features, time series features, and situation features. Cloud patch features based on Cb tracking allow extraction of 19 features, which are composed of four types: coldness features, geometric features,

TABLE 2: Cloud characteristics derived from geostationary imagery.

Type	Features	Number	Characters	Equation [#]	This study	Hong et al., [48] [*]	Arnaud et al., [12] ^{**}	Machado et al., [29] ^{***}	Xu et al., [49] ^{****}
Pixel features	Coldness features	1	Top brightness temperature of Cb pixel (TB)		✓				
		2	Gradient of pixel TB (GT)	$GT_{(x,y)} = \left[\left(TB_{(x+1,y)} - TB_{(x-1,y)} \right)^2 + \left(TB_{(x,y+1)} - TB_{(x,y-1)} \right)^2 \right]^{1/2}$	✓				
		3	Difference of pixel TB over split window channels (SWDT)	$SWDT_{(x,y)} = TB_{1(x,y)} - TB_{2(x,y)}$	✓				
		4	Difference of TB between one IR and WV channel (DIWT)	$DIWT_{(x,y)} = TB_{1(x,y)} - TB_{wv(x,y)}$	✓				
Time evolution features	Change ratio of pixel TB (CTB)	5	Change in pixel cloud type (CPT)	$CPT_{(x,y)} = CT_{t-1(x,y)} - CT_{t(x,y)}$	✓				
		6	Change ratio of pixel TB (CTB)	$CTB_{(x,y)} = \frac{1}{\Delta t} \frac{TB_{t-1(x,y)} - TB_{t(x,y)}}{TB_{t-1(x,y)}}$	✓				
Situation features	Deviation to convective cloud center (DCCC)	7	Deviation to convective cloud center (DCCC)	$DCCC_{(x,y)} = \left((x_0 - x)^2 + (y_0 - y)^2 \right)^{1/2}$	✓				

TABLE 2: Continued.

Type	Features	Number	Characters	Equation [#]	This study	Hong et al., [48] [*]	Arnaud et al., [12] ^{**}	Machado et al., [29] ^{***}	Xu et al., [49] ^{****}
Cloud patch features	Coldness features	8	Minimum TB of a cloud patch ($T_{\min}PD$)	$T_{\min}PD = \min_{(x,y) \in A} \{TB(x, y)\}$	✓	✓		✓	
		9	Mean TB of a cloud patch ($T_{\text{mean}}PD$)	$T_{\text{mean}}PD = \sum_{(x,y) \in A} \{TB(x, y)\} / N$	✓	✓		✓	
		10	Difference in TB over split windows for a Cb patch (DSWT)	$DSWT = T_{\text{mean}}PD_{\text{IR1}} - T_{\text{mean}}PD_{\text{IR2}}$	✓				
		11	Difference in TB over IR and WV windows for a Cb patch (DIWT)	$DIWT = T_{\text{mean}}PD_{\text{IR1}} - T_{\text{mean}}PD_{\text{WV}}$	✓				
		12	Clouds patch area (A)	$A = N \times \text{pixel resolution}$	✓	✓	✓	✓	✓
		13	Perimeter (PERI)	$PERI = N_{\text{bound}} \times \text{pixel resolution}$	✓	✓		✓	✓
		14	Geometric center (x_{Geo} , y_{Geo})	$x_{\text{Geo}} = \sum_{i=1}^N x_i, y_{\text{Geo}} = \sum_{i=1}^N y_i$	✓				✓
		15	Gravitational center (x_{Gra} , y_{Gra})	$x_{\text{Gra}} = \frac{\sum_{i=1}^N TB_{li} \times x_i}{\sum_{i=1}^N TB_{li}}, y_{\text{Gra}} = \frac{\sum_{i=1}^N TB_{li} \times y_i}{\sum_{i=1}^N TB_{li}}$	✓			✓	✓
		16	Shape index of geometric momentum (SIGM)	$SIGM = I/I_0, I = \sum_{i=1}^N [(x - x_{\text{Geo}})^2 + (y - y_{\text{Geo}})^2]$	✓		✓		
		17	Shape index of the perimeter (SIP)	$SIP = PERI/PERI_0$	✓				
Texture features		18	Eccentricity (ECCT)	$ECCT = c/a$	✓	✓		✓	✓
		19	Boundary steepness (BS)	$BS = \frac{\sum_{i=1}^{N_{\text{bond}}} \mu_b(i)}{N}$	✓				
		20	Standard deviation of the TB of a cloud patch (STD)	$STD = \left\{ \sum_{(x,y) \in A} [TB(x, y) - T_{\text{mean}}PD]^2 / (N - 1) \right\}^{1/2}$	✓	✓			✓
		21	Gradient of cloud TB (TOPG)	$TOPG = \sum_{i=1}^N \frac{1}{\mu(i)} / N$	✓	✓			✓

TABLE 2: Continued.

Type	Features	Number	Characters	Equation [#]	This study	Hong et al., [48] [*]	Arnaud et al., [12] ^{**}	Machado et al., [29] ^{***}	Xu et al., [49] ^{****}
Dynamical features		22	Life stage of a cloud patch (L)		✓			✓	
		23	Horizontal moving speed of a Cb patch (HMSP)	$HMSP = \sqrt{(x_0 - x_1)^2 + (y_0 - y_1)^2} / \Delta t$	✓			✓	
		24	Horizontal moving direction of a cloud patch (HMDP)	$HMDP = \arctg((y_0 - y_1)/(x_0 - x_1))$	✓			✓	
		25	Cloud growth rate (CGR)	$CGR = A_t / A_{t-1}$	✓				
		26	Vertical moving character of a Cb patch (VMCP)	$VMCP = (T_{mean} PD_0 - T_{mean} PD_1) / T_{mean} PD_0$	✓				

[#] TB₁, TB₂, and TB_{WV} are the brightness temperature (TB) of three infrared (IR) channels (IR1, 10.3–11.3 μm; IR2, 11.5–12.5 μm; and WV 6.3–7.6 μm), respectively; CT_t is the cloud type on the current (*t*) image, and CT_{t-1} is the corresponding cloud type on the previous (*t* − 1) image; Δ*t* is typically 1 hour. (x₀, y₀) is the center of Cb patch. The center of the Cb patch can be the geometric center (X_{Gco}, Y_{Gco}) or the gravitational center (X_{Gra}, Y_{Gra}); *N* is the number of pixels in a Cb patch; N_{bound} is the number of pixels on the boundary of a Cb patch; *I* is the geometric momentum of a cloud patch, and I₀ is the geometric momentum of a round patch with the same size; PERI is the perimeter of a cloud patch, and PERI₀ is the perimeter of a round patch with the same area; *c* is the distance between the focus and the center of cloud patch, and *a* is the length of the long axis; μ₀(*i*) is the distance from pixel *i* on the Cb cloud patch boundary to the corresponding position on the warmer cloud patch boundary; μ(*i*) is the distance from pixel *i* on the boundary to the shooting top (*T*_{min} PD).

^{*} Hong et al. [48] extracted the following additional parameters: compactness, mean value of local standard deviation of cloud patch (MSTDS), and gray images' texture (angular second moment, contrast, entropy, etc.).

^{**} Arnaud et al. [12] extracted the following additional parameters: maximum length, maximum width, volume index, position of the front edge, and angle between the principal axis of the cloud and the *x*-axis.

^{***} Machado et al., [29] extracted the following additional parameters: area overlap fraction with possible antecedent, average (weighted) difference of all parameters. The dynamical features refer to the MCSs over America.

^{****} Xu et al. [49] extracted the following additional parameters: maximum temperature difference from IR threshold, mean temperature difference from IR threshold, and maximum entropy.

texture features, and cloud dynamic features. Cb dynamic features are composed of life stages and movement parameters. All cloud parameters obtained for each Cb patch are stored in a text file (.txt format), and some dynamical features are stored in an image file (.bmp format).

The cloud features can be described as follows.

3.1. Pixel Features. The height of cloud top by the brightness temperature (TB) and the convection strength by gradient of the TB (GT) are two parameters indicating cloud coldness feature. Three parameters of TB of three infrared channels (TB_1 (10.3–11.3 μm), TB_2 (11.5–12.5 μm), and TB_{WV} (6.3–7.6 μm)) are used in this paper. GT is the gradient of TB for three infrared channels with a window size of 3×3 pixels, centered on pixel $i(x, y)$. Normally, clouds in the development stage correspond to a high cloud top, which can be indicated by less TB and more GT, and vice versa for clouds in the stable stage.

The difference of the TB (DT) can indicate the height and developmental character of convective clouds and is usually used to discriminate Cb and other underlying clouds. The DTs in this study are composed of two parameters: difference of pixel TB over split window channels (SWDT) and difference of TB between one IR and WV channel (DIWT). The former one is the difference in TB over split window channels (IR channels 1 and 2) and the latter one is the TB difference between IR channel 1 and the WV channel.

Change in pixel cloud type (CPT) and change in the ratio of pixel TB (CTB) are two parameters to show the time evolution features of Cb patch. CPT is the cloud type on the current image (CT_t) minus the corresponding cloud type on the previous image (CT_{t-1}), and it can indicate the conversion of cloud type. Six types of clouds (low-level clouds, midlevel clouds, thin cirrus, thick cirrus, multilayer clouds, and cumulonimbus) have been assigned values of 2–7 individually based on previous work of cloud classification [46]. CTB can be used to illustrate the cloud development on the vertical height for strong convection corresponding to the cold cloud top.

The precipitation characters of Cb are always related to the deviation of the convective cloud center (DCCC). For example, heavy precipitation may occur not only in the convective center but also on the front of convective cloud patches. Thus, this study extracted two situation parameters, $DCCC_1$ and $DCCC_2$, according to the geometric center (X_{Geo}, Y_{Geo}) and gravity center (X_{Gra}, Y_{Gra}).

3.2. Cloud Patch Features. The coldness feature of cloud patch contains four parameters: minimum TB of a cloud patch ($T_{min}PD$), mean TB of a cloud patch ($T_{mean}PD$), difference in TB over split windows for a Cb patch (DSWT), and the difference in TB over IR and WV windows for a Cb patch (DIWT). Similar to the cloud on pixel level, rapid uplifting cloud patch has less $T_{min}PD$ and $T_{mean}PD$. DSWT and DIWT can indicate the developmental character of Cb with the information of cloud height and water vapor content.

The geometric feature of Cb clouds can be indicated by cloud patch area (A), cloud patch perimeter (PERI), shape

index of geometric momentum (SIGM), shape index of the perimeter (SIP), and eccentricity (ECCT). SIGM is the ratio of the geometric momentum of a cloud patch I to that of a round patch with the same size (I_0). SIP is the ratio of perimeter (PERI) of a cloud patch to that of a round patch with the same area ($PERI_0$). Normally, Cb in the early stage are always small and nearly round with low values for those geometric parameters compared to Cb in the developing and splitting stages, according to the observation.

The cloud texture/structure features on precipitation can be illustrated with three parameters: boundary steepness (BS), standard deviation of the TB of a cloud patch (STD), and gradient of cloud TB (TOPG). BS measures the temperature gradient along cloud patch boundary, and STD shows the standard deviation in a cloud patch. TOPG is the average temperature gradient from the overshooting top ($T_{min}PD$) to each pixel on a Cb patch boundary.

Dynamic features of cloud can be indicated by 5 parameters, namely, life stage factor of the cloud patch (L), horizontal moving speed of the cloud patch (HMSP), horizontal moving direction of the cloud patch (HMDP), cloud growth rate (CGR), and the vertical moving character of the cloud patch (VMCP). HMSP is the displacement of the cloud patch centers between two successive images, while HMDP is a measure of the displacement of the cloud patch center. CGR is the ratio of the area of a current cloud patch (A_t) to that of a previous one (A_{t-1}). VMCP can be indicated by the ratio of the average TB of a current Cb patch ($T_{mean}PD_0$) to that of a previous one ($T_{mean}PD_1$), for cloud top TB reflects the height of Cb. The life stages of Cb patches can be divided into 8 (Figure 2), which was also shown in Liu et al.'s previous work [50].

The technique for parameter estimation used in this study is similar to that used by Arnaud et al. [12] and Hong et al. [48]. Parameters such as the cloud patch growth rate (CGR) and the vertical moving character of a cloud patch (VMCP), as well as the introduction of Cb extraction based on cloud classification, are additions by this study. It should be noted that some cloud patch parameters, such as BS, STD, and TOPG, may not be very useful for early Cb clouds considering that some Cb in the initial stage are always on a scale of ~ 1 –2 pixels.

4. Results

Because of the great spatial and temporal variation in cloud type, location, shape, and height, it is hard to use other satellites as a reference comparison for different scanning areas of geostationary satellites and limited frequency of polar-orbiting satellites, not to mention that there are no mature satellite-based Cb tracking products. Similarly, it is also not proper to use radar data for comparison because of their limited coverage area, while geostationary satellites observe clouds globally. Therefore, to evaluate the proposed Cb detection and tracking method, the tracking results of 8 cases are compared with their respective cloud classification maps. Another method of assessment is to examine the temporal evolution of the cloud parameters for continuous

FIGURE 2: Diagram of the life stages of a cloud patch (L). (a)–(c) demonstrate birth and straightforward continuations for a single cloud patch; (d)–(h) show complicated Cb patches with other minor splits, mergers concerned. (a) The birth of a new Cb patch (L1). There is no previous corresponding Cb patch for the current Cb patch; (b) development of single cloud patch (L2). It is characterized with straightforward continuation of a Cb patch with area increasing; (c) dissipation of single cloud patch (L3). It is the same as L2 but with area decreasing; (d) merge of complex cloud patch (L4). A Cb patch is a few Cb patches merger; (e) dissipation into several Cb patches (L5). A Cb patch breaks up into several Cb patches; (f) development of complex Cb patch (L6); a Cb patch simultaneously breaks up and absorbs another preexisting cloud while absorption takes the main trend; (g) dissipation of complex cloud patch (L7). Similar to (f) while the dissipation takes the main trend; (h) uncertain cloud patch (L8). Similar to (f) while there is no obvious dissipation process.

evolution indicating consistent tracking. This also allows, for example, the evaluation of the cloud development characteristics by cross-comparison of different parameters.

In Section 4.1, the results of the cloud classification and segmentation of Cb are presented. In Section 4.2, cloud tracking results and some dynamic parameters are shown. The time evolution of Cb patch parameters for one case is given in Section 4.3.

4.1. Results of Cloud Classification and Segmentation. Figure 3 displays an application of the proposed algorithms to a Cb event at 03:00 UTC on July 4, 2007. Figures 3(a)–3(b) show two FY-2C cloud imageries at consecutive time steps. Figure 3(c) is the result of the cloud classification which indicates that convective storms were rapidly developing throughout the tropics and midlatitudes at 03:00 UTC on July 4. According to the previous cloud classification validation

test [46], the ANN model can detect Cb with approximately 90.74% accuracy (Table 1), compared to 76.49% for the FY-2C operational product. The cloud classification results obtained thus far have been encouraging.

Figure 3(d) shows Cb patches segmented from cloud classification imagery, and the varying color indicated different life stages, which is analyzed later in this paper. To further understand the proposed SRG method, this study compared it to a traditional TB threshold-based SRG method with a MCCs case (Figure 4). Reasons for limiting to the MCCs case lie in the fact that there exists a definite TB threshold of -52°C for MCCs according to its definition [51] while there is no acknowledged TB threshold for other clouds, such as MCSs. The results show that the proposed SRG method can provide differentiating Cb well from multilayer clouds compared to the TB threshold-based method.

The above results show that the detection of homogeneous Cb clusters, the first objective in Cb tracking, can be

FIGURE 3: Result of the Cb tracking and dynamical parameters of cloud patch at 03:00 UTC on July 4, 2007. (a) Synthesis map of IR1, IR2, and WV at 02:00 UTC of July 4, 2007. (b) The same as (a) but for 03:00 UTC July 4, 2007; (c) cloud classification results (C1: stratocumulus and altocumulus; C2: altostratus and nimbostratus; C3: mixed cloud; C4: cirrostratus; C5: thick cirrus; C6: cumulonimbus); (d) life stages (L) of Cb. L1, L2...L8 means the same as in Figure 2. Red star shows a Cb patch with gravitational center (27.52°N, 103.85°E); (e) vertical moving character of Cb patches (VMCP); (f) horizontal moving speed of cloud patches (HMSP); (g) horizontal moving direction of cloud patches (HMDP); (h) cloud growth rate (CGR).

FIGURE 4: Segmentation result of the Cb and mesoscale convective complexes (MCCs) (03:00 UTC on July 3, 2008). (a) IRI; (b) segmented MCCs using -52°C as TB threshold; (c) segmented Cb using the proposed SRG method with ANN classification as preprocess; (d) the same as (c) but for segmented multilayer cloud. The color of cloud patches in (b), (c), and (d) is generated randomly.

achieved by combining ANN cloud classification and SRG segmentation. The main reason lies in the fact that SRG method is not sensitive to the TB threshold as the traditional SRG method is, for the preprocess of ANN cloud classifiers reduces hundreds of pieces of float data in satellite imagery data to several pieces of integer data.

4.2. Cloud Tracking and Characterization. Figure 5 is the POD, FAR, and CSI of cloud tracking results of 30 FY-2C imageries (05:00 UTC on 5 July to 10:00 UTC on 4 July). It shows that the average POD, FAR, and CSI of the Cb are 67.18%, 15.38%, and 59.88%.

Figures 3(d)–3(h) show five Cb dynamic parameters (L, HMSP, HMDP, CGR, and VMCP). The main reason for limiting the number of parameters to 5 is that other parameters used in this study are similar to those used by Arnaud et al. [12], although there are some differences in their definitions. These 5 parameters, along with the extraction of Cb based on cloud classification, are the contributions of this study to the presently used scheme. In addition, they can be used as a prediction index for hurricane because of their close relationship to the potential of heavy rainfall. Figures 3(d)–3(h) show that the life stages and moving characteristics of Cb patches vary greatly. Taking the cloud stage factor L as example, it can be seen that the life stages L1 (the birth of a new cloud patch), L2 (development of a single cloud patch),

FIGURE 5: POD, FAR, and CSI of the Cb tracking algorithm for 30 imageries (05:00 UTC on 5 July to 10:00 UTC on 4 July).

and L4 (merging of complicated cloud patches) are the most common in this case. Occurrences of L7 (development of complicated Cb patches) and L8 (uncertain cloud patches) are

relatively rare and are often found in a series of Cb patches that developed in large-scale events such as hurricanes. According to some statistical analyses, the cloud life stages are closely related to Cb rainfall intensity and probability, and the relationship can be used in precipitation estimation [51].

For demonstration purposes, 8 cases of Cb showing distinct life stages (L1, L2...L8) from 03:00 UTC on July 4, 2007, are used to assess the performance of the proposed method (Figures 6(a)–6(h)). Figures 6(a)–6(c) show cases of Cb patches that develop simply, while Figures 6(d)–6(g) show cases with minor Cb splits and mergers. Figure 6(h) shows a case of uncertain life stage for there are many simultaneous major splits and mergers.

As shown in Figures 6(a1)–6(a3), the Cb patch marked with black cross (Figure 6(a3)) is a newborn patch that was only a weak convective initiation system in previous maps (Figure 6(a1)). Figures 6(b)–6(c) show that the Cb patches located in the center of the picture developed or dissipated simply, while Figures 6(d)–6(g) display similar developmental characteristics as Figures 6(b)–6(c), except with a few minor splits and mergers. Figure 6(h) shows a case whose development and dissipation are uncertain for there are many mergers and splits of similar intensities. These results show that the configuration and development stages of Cb identified by the algorithm are close to reality.

4.3. Time Evolution of Various Parameters. The temporal evolution of a Cb case on July 3–4, 2007, in southwest China (27.5°–29.5°N, 99°–103°W) was analyzed to demonstrate the proposed cloud tracking method. The location of it at 03:00 UTC on 4 July was marked by a red star in Figure 3(d).

(1) *Temporal Evolution of Coldness Features.* The $T_{\text{mean}}^{\text{PD}}$ and $T_{\text{min}}^{\text{PD}}$ of the Cb patch show similar variations (Figure 7(a)): both decrease after 05:00 UTC on 3 July and reach their minima at approximately 11:00 UTC. The temperatures then fluctuate while generally rising until 02:00 UTC on 4 July. The values of SWDT and DIWT are negative and have similar peak times to those of $T_{\text{mean}}^{\text{PD}}$ (Figure 7(b)).

(2) Temporal Evolution of Geometric Features

(i) *Area and Perimeter.* Figure 7(c) shows that there was a continuous increase in cloud area until 08:00 UTC on 3 July. After that, the cloud area continued to increase rapidly from 08:00 to 10:00 UTC with some Cb mergers. In the next stage, at 14:00 UTC, the cloud cell dissipated. Then, three similar life cycles occurred between 14:00 UTC and 09:00 UTC the next day, when the cloud cell disappeared. During these life cycles, this Cb cell experienced many minor splits and mergers that were identified by the proposed method.

(ii) *Displacement of the Geometric and Gravitational Centers of the Cb Patch.* Representing the simultaneous evolution of the center position of the Cb patch is useful because cloud development can be related to geographical characteristics. Figure 7(d) shows the analysis of the system trajectory. It shows that, in most cases, the system propagates from northwest to southeast. On the whole, the geometric centers

are consistent with the gravitational centers, but more smoothness and continuity can be seen in the displacement of gravitational centers of small cloud patches. This finding indicates that the initial stages of Cb patches are always associated with irregular and rapidly changing shapes. Discontinuities that occurred at four sites (with gravitational centers 29.5°N, 99.2°W; 28°N, 100.5°W; 27.5°N, 102°W; and 27.5°N, 103°W) were due to the merger of some minor Cb patches previously located ahead of the perturbation.

(iii) *Shape Character.* Figure 7(e) shows that the SIGM experienced successive increases and decreases between 06:00 UTC on 3 July and 01:00 UTC on 4 July corresponding to the modulations of the SIP. The variation is the opposite for the other two periods, 05:00–0600 UTC on 3 July and 01:00–09:00 UTC on 4 July, which is related to the birth of a small Cb patch and the dissipation of a few complicated Cb patches. ECCT varied from 0.9 to 1.0 and experienced similar variations to those experienced by SIP and SIGM.

(3) *Temporal Evolution of Texture Features.* Figure 7(f) shows that the TOPG increased from 05:00 UTC on 3 July reached its peak at 11:00 UTC, and then decreased until 18:00 UTC on 4 July. Another increase and decrease took place thereafter. The peaks appear to correspond to the shape parameters, SIP, and the merging and dissipation of other minor Cb cells. The other two textural features, STD and BS, show a continuous similar variation TOPG. Overall, the major peak of STD occurred first, followed by peaks of BS and TOPG. BS always peaked approximately one hour ahead of TOPG, which may be an important indication for precipitation prediction.

(4) Temporal Evolution of Cloud Dynamical Features

(i) *Cloud life stage:* Figure 7(g) shows that the Cb patch was born at 05:00 UTC on July 3, 2007. It grew simply (L2) and developed rapidly by merging with other Cb cells (L4 and L6) before 00:00 UTC on 4 July. Thereafter, it decreased in size and disappeared at 09:00 UTC on 4 July.

(ii) *Motion character:* Figures 7(h)–7(i) show that the value of CGR evolved with the change of life stage: CGR was positive for developing Cb stages (L2, L4, and L6) and was negative for dissipating Cb stages (L3, L5, and L7). The major peak of horizontal moving directions (HMDP) occurred at the moment of merging and dissipation of other minor cloud patches. The horizontal moving character (HMSP) showed similar variations to the vertical moving character (VMCP). Generally, a greater absolute value of VMCP is associated with greater HMSP, which indicates stronger convective systems that produce heavy rainfall.

FIGURE 6: Continued.

FIGURE 6: Cb patches in various life stages. The analyzed Cb patches are always located in the center of picture and their gravitational centers are marked with black criss-cross. The first column (a1, b1... h1) is the classification results at 02:00 UTC of July 4, 2007; the second column (a2, b2... h2) is the same as the first column but for 03:00 UTC; the third column (a3, b3... h3) is the determination of life stages, respectively (a3: L1; b3: L2; c3: L3; d3: L4; e3: L5; f3: L6; g3: L7; h3: L8). L1, L2... L8 means the same as that of Figure 2.

5. Conclusion and Discussion

This study proposed a new approach to track Cb from FY-2C images, which consists of three stages: identifying Cb pixels based on ANN cloud classification, segmenting Cb patches with a seeded region growing algorithm (SRG), and tracking Cb patches using a cross-correlation-based approach. Then, 27 cloud parameters (7 pixel parameters and 20 cloud patch parameters) were extracted to characterize Cb behavior at the pixel and patch levels. The performance of the Cb detection and tracking method was demonstrated with 8 cases of distinct life stages and the time evolution of Cb patch parameters for one case.

The result shows the following.

- (1) The cloud classification based Cb tracking method reduces the uncertainty in Cb identification for it is

not sensitive to the TB thresholds which are widely used in the traditional SRG method.

- (2) The proposed method is not only capable of locating and tracking Cb until dissipation, but is also capable of dealing with more complicated systems related to moving disturbances.
- (3) Analysis of the evolution of Cb patch parameters demonstrates some interesting results, such as a direct correspondence among cloud coldness features, geometric features, texture features, and dynamic features. Characterizing Cb from geostationary satellite and analysis can provide deep insight into the precipitation estimation and nowcasting.

Because this is the initial part of the current research that is more focused on the methodology, more complex and advanced scenarios (e.g., individual cloud patches) still need to be investigated and comprehensively evaluated. In

FIGURE 7: Continued.

FIGURE 7: Temporal evolution of cloud patch features for a Cb patch which is marked with a red star in Figure 3. (a) Minimum TB ($T_{\min}$ PD) and mean TB (T_{mean} PD); (b) difference in TB over split windows (DSWT) and difference in TB over IRI and WV (DIWT); (c) cloud area and perimeter; (d) displacement of geometric center and gravitational center; (e) eccentricity (ECCT), shape index of geometric momentum (SIGM), and shape index of the perimeter (SIP); (f) gradient of cloud TB (TOPG), boundary steepness (BS), and standard deviation (STD); (g) cloud life stages (L). L1, L2...L8 means the same as in Figure 2; (h) cloud growth rate (CGR) and horizontal moving direction (HMDP); (i) vertical moving character of a Cb patch (VMCP) and horizontal moving speed (HMSP).

addition, some improvement can be made in the near future. For example, some new subpixel cloud tracking approaches, such as the variational echo tracking (VET) and optical flow method, can be applied to improve the accuracy of cloud tracking based on the temporal, spatial, and spectral character of satellites. In addition, considering that the ANN classifier needs numerous samples which depend on the experience of experts, more objective cloud classification methods using time series information of geostationary satellite are needed to improve the algorithm's capability of detecting Cb. Moreover, the time evolution of cloud

dynamical features corresponding to the potential of Cb for heavy rainfall can be analyzed systematically with the extraction of more physically meaningful precipitation parameters. Therefore, efforts are underway by the authors to improve the algorithm by testing more scenarios and we will report our findings in the future.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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