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NOTES AND CORRESPONDENCE

Comparison of a Split-window and a Multi-spectral Cloud Classification for MODIS Observations

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Abstract

Results of the split-window cloud retrieval method and the new Meteosat Second Generation cloud analysis method (MSG/CLA), have been compared for MODIS data over the west Atlantic Ocean. Very good agreement is obtained for the classification of optically thick ice and water clouds. Differences are found for thin cirrus, thin water clouds and at cloud edges. These differences are explained by the fact that MSG/CLA also uses spectral channels of 3.9, 6.2, and 8.7 μm in addition to the split-window, which provides information over and above the split-window observations. Some of the disagreement at cloud edges is interpreted as inter-channel miss-alignment. The analysis in this study also confirms that an optically thin water cloud can be correctly classified by the MSG/CLA method.

1. Introduction

Cloud analysis and classification inferred from a satellite image provides important information to operational nowcasting, and also constitutes an essential first step towards the retrieval of other products either inferred from the cloudy or the clear-sky radiances. Cloud classifications have been developed for global climate applications (Rossow and Schiffer 1991), operational meteorology (Saunders and Kriebel 1988; Karlsson 1997) and as an operational preprocessor for the derivation of other products from satellites (Lutz 1999). Objective cloud type classification maps are used as a neph-analysis to supplement weather forecasts. Cloud classification can be used as proxy for other products; for instance, Inoue and Kamahori (2001) have shown that the vertical structure of relative humidity is statistically related to the occurrence of cumulonimbus, cirrus, mid-level, low-level and clear sky, respectively. Inoue and Ackerman (2002) per-

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formed a climatological study relating the radiation budget at the top of the atmosphere from ERBE to each cloud type inferred from AVHRR data. The importance of cloud analysis in the process study of deep convection over the tropics was demonstrated by Inoue and Wu (2001). They studied deep convective cloud in terms of cloud type. Such an analysis could have some bearing on recent and controversial study concerning the 'IRIS effect' proposed by Lindzen et al. (2001).

This paper compares two mature cloud classification methods. The first one, developed by Inoue (1987; 1989), is a simple cloud type classification method using the split window (11 and 12 μm) based on his detection of differential absorption of ice clouds in the split window channels (Inoue 1985). With his method one can basically classify cirrus clouds and optically thick clouds. Important to the current paper is that Inoue (1987; 1989) neglected optically thin water cloud, which has the same differential absorption characteristic for the split window. This appeared justified because water clouds in the lower troposphere tend to be optically thick for relatively small geometrical thickness. However, geometrically thin mid-level clouds such as alto-stratus are also in pure water phase and optically thin too. The characteristics of the split-window for these cloud types have not been studied so far. Furthermore, it is of interest to analyse which cloud type, as derived with another cloud analysis method, corresponds to the so-called N-type from the split-window method. Previously the N-type clouds have been considered as low level cloud overlaid by thin cirrus, non-black body cloud or partial cloudiness within the FOV at the edge of cloud (Inoue 1987; 1989).

The split-window technique is compared with a newly developed cloud classification (Lutz 1999, Lutz 2002) that will be used operationally with the new European geostationary satellite—Meteosat Second Generation (MSG). This method makes use of all twelve spectral channels of MSG, which have center wavelengths at 0.6, 0.8, 1.6, 3.9, 6.2, 7.3, 8.7, 9.7, 10.8, 12.0, and 13.4 μm, respectively, and in addition a broadband high resolution visible channel (Schmetz et al. 2002). This paper investigates the contribution of different channels to the cloud type classification by comparing the MSG method and the split-window method. A focus is on the classification of thin ice and thin water clouds. Both methods are applied to direct broadcast data from the MODIS (Moderate Resolution Imaging Spectroradiometer) instrument on the TERRA satellite, received at the SSEC (Space Science Engineering Center) in Madison, Wisconsin (Strabala et al. 2002).

2. Description of the algorithms

2.1 Split-window method

In this study, nine cloud types are classified using three thresholds of blackbody brightness temperature for channel 10.8 μm (TBB11), and the two thresholds of brightness temperature difference for the channels 10.8 μm and 12.0 μm (BTD11-12 = TBB11-TBB12) (Fig. 1). The threshold for the clear/cloudy decision is determined from the spatial coherence method (Coakley and Bretherton 1982) in combination with ECMWF analysis data of the surface temperature. The temperature at 400 hPa and 600 hPa of ECMWF analysis are used as the thresholds for high- and mid-level cloud. The BTD11-12 threshold for cirrus cloud is set to 2.5 K considering the water vapor amount over the cloud free area. The BTD11-12 threshold for optically thick cloud is set to 1 K considering the temperature resolution at lower TBB. The correspondence between cloud type and cloud number are shown in Fig. 1, although the name of cloud types are arbitrarily for this study.

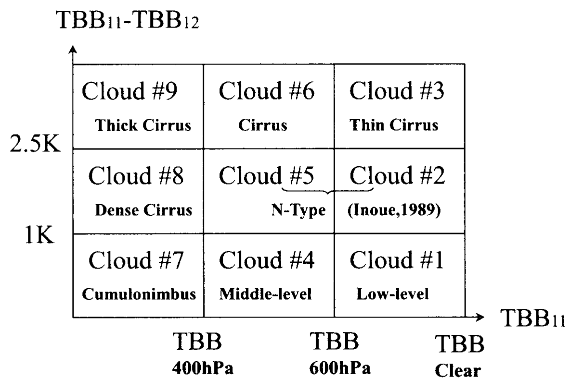

Fig. 1. Classification matrix of the cloud types used by the split-window method. The cloud number and cloud type are shown, however, correspondence between cloud number and cloud type is arbitrarily.

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2.2 MSG scenes and cloud analysis method

The MSG scenes and cloud analysis algorithm has been described in detail by Lutz (1999 and 2002). The algorithm is based on well-known threshold techniques (e.g., Saunders and Kriebel 1988). The cloud processing is split into a cloud detection (Scenes Analysis, MSG/SCE) and into a detailed cloud analysis (MSG/CLA).

The MSG/SCE algorithm has been designed to perform the operational cloud detection with the multi-spectral radiance observations from METEOSAT Second Generation (MSG). It derives a cloud mask on pixel basis for every 15 minutes and generates quality information of the cloud/no cloud decision. The MSG/SCE is based on a threshold technique, which can use up to 29 threshold tests. These tests are applied in a parallel mode, which means that regardless of whether a test detects a cloud, the other tests will still be applied. The reason for this is to generate a quality indicator providing a level of confidence in the results of the cloud detection. However not all tests are applied, since some of them are redundant and therefore are used as a backup, if channels fail and the corresponding tests cannot be applied. The thresholds are generated dynamically by computing the thermal infrared radiances from short-term forecast data with the help of a radiative transfer model (RTM) (Tjemkes and Schmetz 1997). For the solar channels, reflectance thresholds are frequently updated on the basis of previous classifications.

The selection of the appropriate tests and the tuning of the thresholds, are done according to the situation at the pixel location, e.g., time of the day (day/night/twilight), location (land/sea/coast) and special situation (e.g., sunglint, high elevation, cold surfaces).

The MSG/CLA algorithm derives detailed cloud information on pixel basis for every 15 minutes. The MSG/CLA algorithm is also based on a threshold technique, where the selection of the tests is depending on the location, time of the day and synoptic situation. The algorithm works with "dynamic" thresholds similar to the MSG/SCE algorithm. The MSG/CLA algorithm derives the following detailed cloud information:

- Cloud phase—using channels 0.6, 1.6, 3.9, 8.7, 10.8 and 12.0 μm
- Cloud top height (pressure and temperature) with direct method using channel 10.8 μm for opaque clouds and the rationing methods using channels 6.2, 7.3, 10.8 and 13.4 μm for semi-transparent clouds (Menzel et al. 1983)
- semi-transparency flag and effective cloud amount, derived with the height information
- Cloud type information using the derived parameters above, the standard deviation of channel 10.8 μm for Cumulus/Stratus type identification and a combination of channels 3.9 μm and 10.8 μm for Fog/low Stratus identification.

All channels are used to derive the above information, however, the parameters of BTD11-8 and BTD11-6 are introduced here for the following discussion. For water cloud BTD11-8 become small due to the fact that the difference in water particle absorption is small between the two wavelength, but very large for ice particles. The BTD11-6 becomes smaller for ice particles because absorption is similar for both wavelengths, and the cloud is high enough, that the water vapor absorption in the atmosphere above is significantly smaller compared to the clear sky case. On the other hand most of the water clouds will not be seen by this channel combination, because these clouds cannot be seen in the 6.2 μm channel.

The cloud top height is used to separate the cloud types into three basic categories, i.e., high-, mid-, and low-level cloud. The cloud phase is used to separate ice clouds from water clouds, and the semi-transparency flag and the effective cloud amount, are providing an indication of the cloud optical thickness.

3. Results

3.1 Basic results of the two methods

MODIS 1 km resolution data are used to compare the cloud type classification performance between the MSG/CLA method and the split-window method. The MODIS instrument is on-board of the TERRA and AQUA satellites in sun-synchronous orbits. The case studied, is located over the West-Atlantic region at a latitude of around 33° North (covering 25°N–40°N, 75°W–55°W) and had been received by a direct read-out station at SSEC in Madison Wisconsin from the MODIS instrument on the TERRA satellite.

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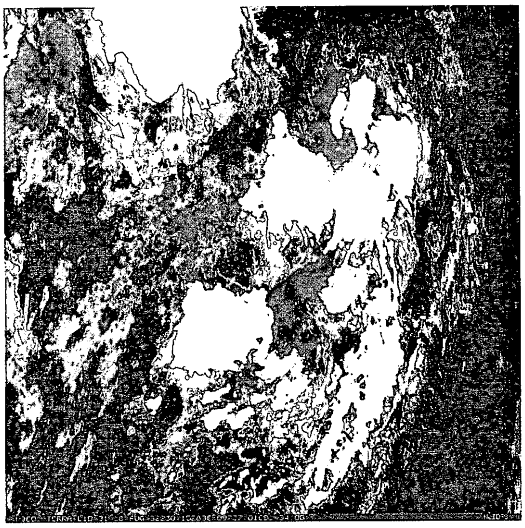

Fig. 2. Cloud type map by the split-window method with: blue = clear ocean, black = cloud #1, yellow = cloud #2, red = cloud #3, grey = cloud #4, green = cloud #5, orange = cloud #6, white = cloud #7, 8, and 9, the red arrows are pointing to thin water clouds.

Fig. 4. RGB Color composite of channel 3.9 μm (red), BTD11-6 (green) and BTD11-8 (blue) with: black = clear ocean, white = optically thick cirrus clouds, green = optically thick mid- and low-level water clouds, bright blue = optically thin cirrus clouds, dark blue = optically thin water clouds and cloud edges, the red arrows are pointing to thin water clouds.

Fig. 3. Cloud classification by the MSG/CLA method with: blue = clear ocean, dark grey = low-level clouds, bright grey = mid-level clouds, white = high-level clouds, the red arrows are pointing to thin water clouds.

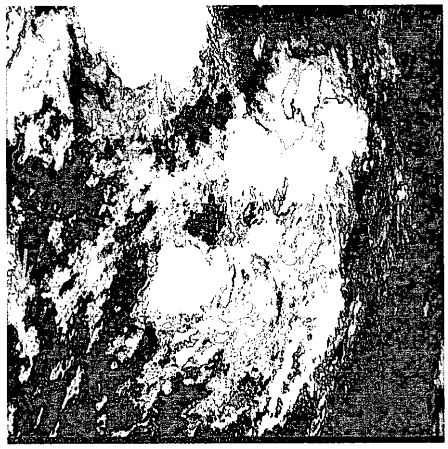

Fig. 5. Comparison of the results of the split-window and the MSG/CLA methods: blue = clear ocean with both methods, black = clear ocean with split-window method but not with MSG/CLA, dark grey = low-level clouds (incl. N-type cloud #2) with both methods, orange = low-level clouds with MSG/CLA but not with split-window method, bright grey = mid-level clouds (incl. N-type cloud #5) with both methods, yellow = mid-level clouds with MSG/CLA but not with split-window method, white = high-level clouds with both methods, red = high-level clouds with MSG/CLA but not with split-window method, the red arrows are pointing to thin water clouds.

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Table 1. Contingency table of the cloud type classification by the two methods

	Split-window low-level cloud	Split-window mid-level cloud	Split-window high-level cloud
MSG-CLA low-level cloud	**69.3%**	2.3%	13.4%
MSG-CLA mid-level cloud	1.6%	**80.9%**	15.9%
MSG-CLA high-level cloud	29.1%	16.7%	**70.7%**

The temperature thresholds to discriminate low-level, mid-level and high-level clouds are derived from ECMWF analysis data for both MSG/CLA and split-window methods. For this study the MSG/CLA algorithm uses MODIS channels at 0.6, 1.6, 3.9, 6.2, 8.7, 10.8 and 12.0 μm that are comparable to 7 out of 12 channels on board of MSG.

The split-window method and the MSG/CLA method have different discriminations of cloud types. In order to map cloud classes onto one another the following approach is adopted: i) low-level clouds are equated from of MSG/CLA with cloud #1 (Fig. 1) of the split-window method, ii) mid-level clouds (of MSG/CLA) are mapped on cloud #4, iii) high-level clouds (of MSG/CLA) are equivalent to cloud #3 + #6 + #7 + #8 + #9. The N-type clouds have no comparable cloud types in the MSG/CLA. Therefore the N-type clouds have been related to all MSG/CLA cloud types.

Figure 2 shows the analyzed area; cloud amounts of cloud #1, #2, #3, #4, #5, #6, #7 + #8 + #9 in that area are 1%, 16%, 12%, 9%, 14%, 20%, and 28%, respectively. For comparison Fig. 3 shows corresponding results of MSG/CLA with the separation of low-, mid- and high-level clouds.

High-, mid- and low-level cloud is compared as indicated above. The cloud types of both methods agree for 72% of the cloud pixels, and disagree for 28%. Details of this comparison are shown in the contingency table (Table 1). The low-level, mid-level and high-level clouds classified by the split-window method correspond to the low-level, mid-level and high-level cloud by the MSG/CLA algorithm as 69%, 81% and 71%, respectively. This suggests that the two methods perform a reasonable correct cloud type classification.

To be able to identify the cloud types more easily by visual inspection and to confirm the results of the two methods, a color composite image is used (Fig. 4). The color composite method uses the channel combination of 3.9 μm, BTD11-6 and BTD11-8, which clearly separates most of the cloud types. In Fig. 4, the black area corresponds to clear ocean, the white area corresponds to optically thick cirrus cloud, the green area corresponds to thick water cloud, the bright blue area corresponds to optically thin cirrus cloud, and the dark blue area corresponds to optically thin water cloud.

3.2 *Discussion of the differences in the results of the two methods*

Figure 5 shows the comparison of the cloud analysis results between the two methods. From Fig. 5 one can clearly see which clouds agree the results of the split-window method and of MSG/CLA, and in which areas different results can be found. The blue, dark grey, bright grey and white area shows agreement between the methods, and the black, orange, yellow and red area indicates disagreement between them. The color code stands for clear (blue/black), low-level cloud (dark-grey/orange), middle-level cloud (bright-grey/yellow) and high-level cloud (white/red), respectively.

Looking at high-level clouds one can see that the cloud #7 + #8 + #9 (high-level cloud types of cumulonimbus, dense cirrus, thick cirrus by the split-window method) corresponds to the high-level cloud by the MSG/CLA algorithm of 94% or better (Table 2). However, cloud #6 (cirrus cloud by the split window method) corresponds

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Table 2. Contingency table for the high-level cloud type classification by the two methods

	Split-window Cloud #3	Split-window Cloud #6	Split-window Cloud #9	Split-window Cloud #8	Split-window Cloud #7
MSG-CLA low-level cloud	58.0%	6.4%	0.0%	0.0%	0.0%
MSG-CLA mid-level cloud	7.8%	35.7%	2.6%	5.9%	4.2%
MSG-CLA high-level cloud	**34.2%**	**57.9%**	**97.4%**	**94.1%**	**95.8%**

to the high-level cloud by the MSG/CLA algorithm of 58%, and cloud #3 (thin cirrus cloud by the split-window method) corresponds to only 34% of MSG/CLA high-level cloud. In most cases the cloud #3 of the split-window method is classified as low-level cloud by the MSG/CLA algorithm. Cloud #6 of the split-window method corresponds to mid-level cloud of the MSG/CLA algorithm by 36%.

For mid-level clouds, one can see from Table 1 that 81% of the cloud #4 (mid-level cloud by the split-window method) corresponds to MSG/CLA mid-level cloud, and that 17% of the cloud #4 is classified as MSG/CLA high-level cloud. Only 2% of cloud #4 is classified as low-level cloud by the MSG/CLA algorithm. Looking at the 17% disagreement between cloud #4 and the high-level cloud class of MSG/CLA, the difference comes from the fact, that BTD11-6 detected these clouds and that the cloud top height assignment indicated a semi-transparent high-level ice cloud.

For the low-level clouds, an agreement of 69% between cloud #1 (low-level cloud by the split-window method) and the MSG/CLA low-level cloud is found. While less than 2% of cloud #1 is classified as mid-level clouds by MSG/CLA, a large amount of cloud #1 is classified as high-level cloud by MSG/CLA (29%). The difference between the split-window method and MSG/CLA mostly occurs at larger scan angles, which indicates that the satellite zenith angle dependency of the split window data should be studied further. As for the mid-level clouds, the MSG/CLA classifies the cloud #1 of the split-window method to high-level clouds based on the data of the 6.2 μm channel. This indicates the effectiveness of the 6.2 μm channel to identify high-level cloud in the MSG/CLA method. However, since the number of low-level cloud is very small in this case (less than 1% of all clouds are cloud type #1), one cannot draw a clear conclusion.

Some differences between the two methods occurs at cloud edges, where BTD11-12 values are relatively larger which indicates ice clouds, but BTD11-8 values are showing indifferent results, and the BTD11-6 values do not show cloud contamination. Thus the MSG/CLA classifies these clouds as low- or mid-level clouds. However, cloud edges are difficult to identify even by human eyes, especially if condensation is still ongoing at the cloud edges.

In case of cloud edges, both BTD11-12 and BTD11-8 show relatively large values, however these values are very close to thresholds chosen for separating ice clouds from water clouds. Therefore, more study is required in the case of cloud edges, since here the BTD11-12 and BTD11-8 indicate slightly larger value than for the central part of clouds. In addition, for the edges of high-level clouds and for some mid-level clouds, BTD11-6 clearly indicates the presence also of clouds in these pixels. Further, most of these critical areas are on the wet side of the clouds, which is the side with a maximum of moisture as indicated by the measurements of channel 6.2 μm. This is common for all cloud edges, independent of the cloud type, it is suggested that this may come from mis-alignment of sensors. It is understood that the co-registration of different spectral channels is not perfect, which leads to small mis-matches of field of views of different channels. The effect of this slight difference in field of view is most pronounced at cloud edges. The mis-alignment should also be studied for the further understanding of cloud type classification.

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3.3 Analysis of N-type clouds

It is interesting to see which cloud types are classified by the MSG/CLA method for the N-type clouds of the split window. The cloud amount of cloud #2 (warmer N-type cloud by the split-window method) is 16% of the total cloud cover. MSG/CLA classifies 74% of this cloud as low-level water cloud, and 26% of this cloud is classified as high-level ice cloud. The cloud amount of cloud #5 (colder N-type cloud by the split-window method) is 14% of the total cloud cover. MSG/CLA classifies 57% of this cloud as mid-level water cloud, and 35% of this cloud as high-level ice cloud.

From the spatial distribution of N-type, it is found that the low-level cloud area of MSG/CLA corresponds to the N-type (cloud #2) of the split-window. The TBB11 values for this cloud area is about 4 K colder than surrounding clear ocean area. However, in visible image these clouds appear not as bright as other water clouds. The BTD11-12 indicates about 2 K difference, therefore the cloud is classified as N-type by the split-window method. The BTD11-8 indicates smaller value, which corresponds to clouds in water phase. The 3.9 μm image shows the cloud more clearly than the visible image. Considering the above, the cloud is defined as very thin low-level water cloud. The BTD11-12 of this cloud is not as large as cirrus cloud criteria but larger than the optically thick cloud criteria. These values of BTD11-12 can be found over a relatively large area and not just at cloud edges.

Generally it is difficult to classify multi-layered cloud cases from satellite observation, especially when optically thick high clouds exist in the field of view. The split-window technique occasionally analyses the N-type and cloud #6 at the edge of the deep convection. As cloud edges of deep convection have a lower effective emissivity the effect of multi-layered clouds might become noticeable. The multi-layered cloud case will be studied in the future.

3.4 Thin water clouds

Cases where the split-window method indicates cirrus but MSG/CLA indicates low-level water clouds could be explained by the presence of optically thin water clouds. In these cases one finds relatively large BTD11-12 values. On the other hand one finds smaller or negative BTD11-8 values indicating water clouds. Therefore, MSG/CLA classifies these clouds as low- or mid-level water clouds. This is supported by the brightness temperature difference between 6.2 μm and 10.8 μm (BTD11-6), which picks up high-level clouds only, since the water vapor channel at 6.2 μm cannot see clouds below 500 to 600 hPa due to the water vapor absorption.

In the split-window method, thin water cloud is not commonly considered, because water clouds are considered as optically thick clouds and also have a geometrical thickness in the order of 100 m or more. However, aircraft measurements (e.g., Schmetz et al. 1983) have shown that marine stratocumulus clouds are often optically thin and horizontally inhomogeneous. The absorption characteristics for water phase clouds are different at 11 μm and 12 μm. Though the difference is smaller than for ice clouds, this feature potentially leads to misclassification. This can be considered as a reason for the difference in the cloud type classification (see also Luo et al. 2002).

Taking into account the results of the different tests used in this study, i.e. BTD11-12, BTD11-8, and BTD11-6, one can conclude that optically thin water clouds are present in this region (as shown by arrows in Figs. 2, 3, 4, 5). The multi-channel MSG/CLA method depicts those clouds due to the multi-channel approach, whereas the split window method has limited skill as it uses only two spectral channels.

4. Conclusions

The comparison of the cloud type classification by the split window and by the MSG/CLA method shows reasonable agreements. For optically thick high-level clouds both methods agree within 94%. For the other clouds, in particular thin water and thin ice clouds, the differences between the two methods are larger. It should be noted that the analysed scene is dominated by high-level cloud (i.e., 60% of the clouds). The main reason for the differences in classifying thin water and thin ice clouds, is that the BTD11-12 values do not show unique results for some of the clouds. In particular this is true for thin water clouds and cloud edges which in some cases are interpreted as thin ice

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clouds with the BTD11-12 test. The reason is that one can clearly identify thin clouds with the BTD11-12 test, however it cannot distinguish between thin ice clouds, thin water clouds and cloud edges. In addition to that some of the clouds do not provide a definitive signal, e.g., for some of the thin water clouds the BTD11-12 difference was too small to interpret the cloud as thin cirrus, but too large to be interpreted as a low-level thick cloud. For these clouds the split-window method has the N-type classification that accounts for such undefined cases.

In order to get a clear interpretation of the different cloud types, one needs additional information, which can be provided by the BTD11-8 and BTD11-6 tests. With the BTD11-8 test the cloud phase can be determined, and consequently thin ice clouds can be separated from thin water clouds. Test BTD11-6 is effective to distinguish between high-level and low-level/mid-level clouds. In the case discussed, the BTD11-6 was particularly useful to separate the cloud edges of mid-level clouds from the thin high-level clouds. The test also helps to identify additional thin ice clouds especially at the edge of a scan, where BTD11-12 and BTD11-8 are not definitive, due to the small differences between the measured values. This is also confirmed by a composite image of channel 3.9 μm, BTD11-6 and BTD11-8 (Fig. 4) that clearly depicts the different cloud types including optically thin water clouds.

In summary, the paper reconfirms the capability of the split-window technique concerning the detection of high-level clouds. It also shows limitations of the split-window method for thin water clouds that can be alleviated by a multi-spectral cloud classification that utilizes a larger number of spectral channels.

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