

SPATIALLY VARYING SPECTRAL THRESHOLDS FOR MODIS CLOUD DETECTION

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1. INTRODUCTION

For many parameters derived from satellite imagery, the accurate detection of clouds is essential. The determination of cloud or no cloud for each pixel is known as a cloud mask. Cloud masks are used to filter out cloudy pixels for clear-sky retrievals such as land and sea surface temperature and total precipitable water, and also to detect clouds for cloud parameter retrievals such as cloud phase and cloud top pressure.

The Moderate Resolution Imaging Spectroradiometer (MODIS) instruments on NASA's Terra and Aqua polar-orbiting satellites provide multiple channels of high spatial resolution (250 m - 1 km) data that are used to generate a cloud mask. The MODIS cloud mask is an Earth Observing System (EOS) standard product that is generated globally, both night and day. However, the MODIS cloud mask has performance limitations in certain situations, prompting an investigation into producing a MODIS cloud mask for regional applications.

Research at the Global Hydrology and Climate Center (GHCC) located within the National Space Science and Technology Center (NSSTC) has produced a robust real-time GOES Imager and Sounder cloud mask (Guillory et al. 1998, Jedlovec and Laws 2001 and 2003, and Haines et al. 2004). The GHCC GOES cloud mask uses composite images to provide both spatially and temporally varying thresholds applied to several cloud tests. This paper discusses the adaptation of the GHCC GOES cloud mask to MODIS data. Following are descriptions of the EOS MODIS cloud mask and the GHCC GOES/MODIS cloud mask algorithm, and validation results generated from manual observations of the cloud mask and corresponding imagery.

2. BACKGROUND

2.1 EOS MODIS Cloud Mask

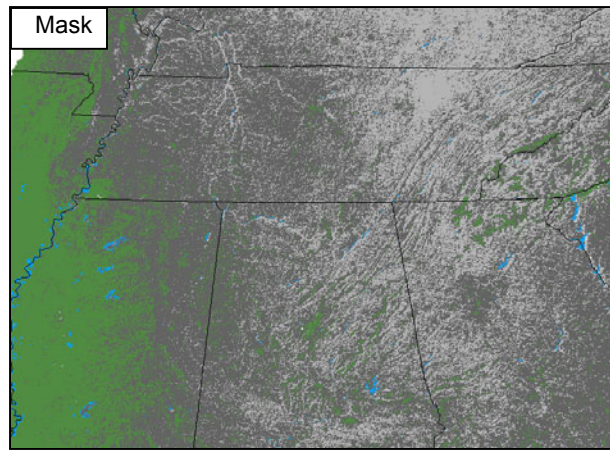
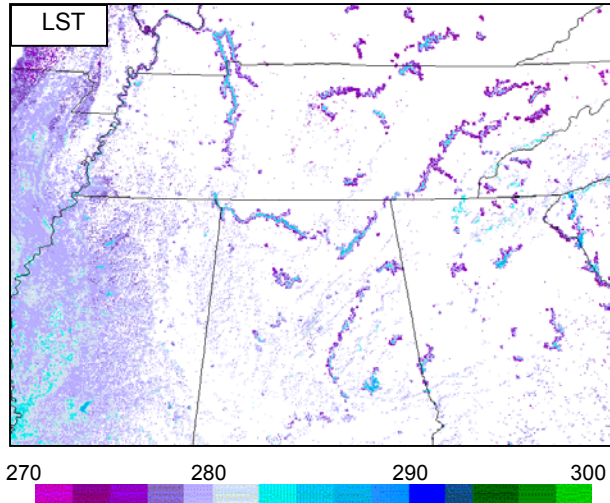
The EOS cloud mask product (MOD35) generated by the MODIS Atmospheric Science Team located at the University of Wisconsin (UW), Madison, uses nineteen spectral channels to perform fourteen tests (Ackerman et al. 2002). The output is not a binary cloud or no-cloud value, but levels of cloud certainty based on

the number of tests that detected a cloud. There is also information within the dataset on whether snow/ice or sun glint is present and if the underlying surface is land or water. There are four cloud certainty levels: cloudy, uncertain clear, probably clear, and confident clear. By providing these different levels, users can customize the cloud mask according to their particular needs. For example, the MODIS Land Science Team derives land surface temperature (LST) only when there is a 99% confidence that the pixel is clear (66% confidence required for lakes and rivers). The Atmospheric Science Team at UW assumes that pixels labeled as cloudy and uncertain clear are cloudy for their atmospheric products such as cloud top pressure.

There are several documented limitations of the MODIS cloud mask (ftp://origin.ssec.wisc.edu/pub/IMAPP/MODIS/Level2/v1.1/Cloud_Mask_Problem_Regions.txt), including problems in semi-arid regions, extreme sun glint regions, high deserts, nighttime polar regions, and nighttime in general. An example of poor performance of the cloud mask at night that directly affects the coverage of the MODIS LST product is shown in Figure 1. This figure shows a nighttime (0735 UTC) LST image, the cloud mask, and an infrared (IR) image for a portion of the southeastern United States. Notice that although the region is clear, as indicated by the IR image, LST was not derived for most of the land pixels because the cloud mask indicated uncertain clear (light gray) or probably clear (dark gray). Regional limitations of the EOS cloud mask exist during the day as well. Figure 2 compares a daytime MODIS cloud mask to a false color composite image (red is snow, white is clouds) for 1652 UTC on 11th January 2004. Notice the over-determination (white indicates cloudy pixels) in several regions including over the snow in Canada, the snow/clear boundary across Kansas, Missouri and Illinois, and at the edge of the swath over New Mexico and Western Texas.

The EOS MODIS cloud mask is a global product and seems to perform fairly well at the global scale. However, it does have some limitations that affect its use for regional applications. Current research in support of NASA's Short-term Prediction and Research Transition (SPoRT) program (Goodman et al. 2004) focuses on improved short term weather forecasts over the continental United States (CONUS) where a more robust detection of clouds is often required. The limitations of the EOS MODIS cloud mask required the development of a regional MODIS cloud mask that would optimize cloud detection for these applications. The paper describes the progress in this effort.

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Cloudy Uncertain Probably Ocean Coastal/ Land Desert
 Clear Clear Clear

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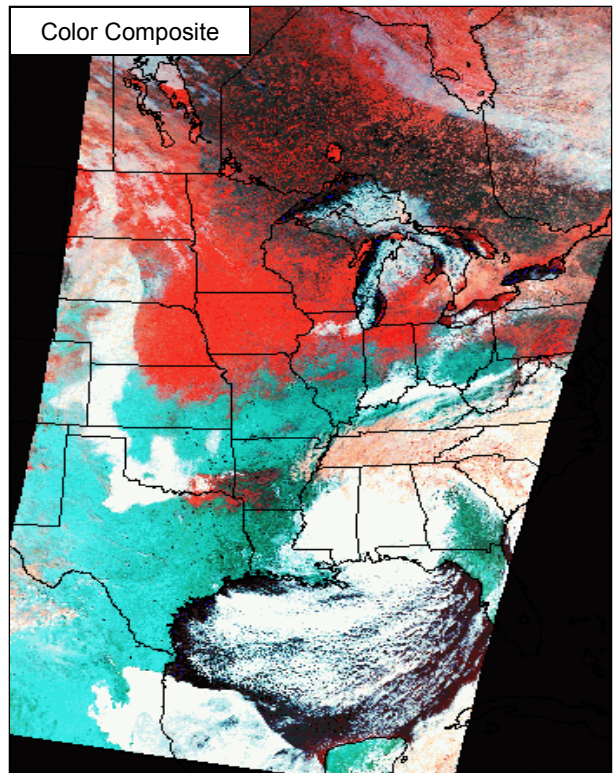
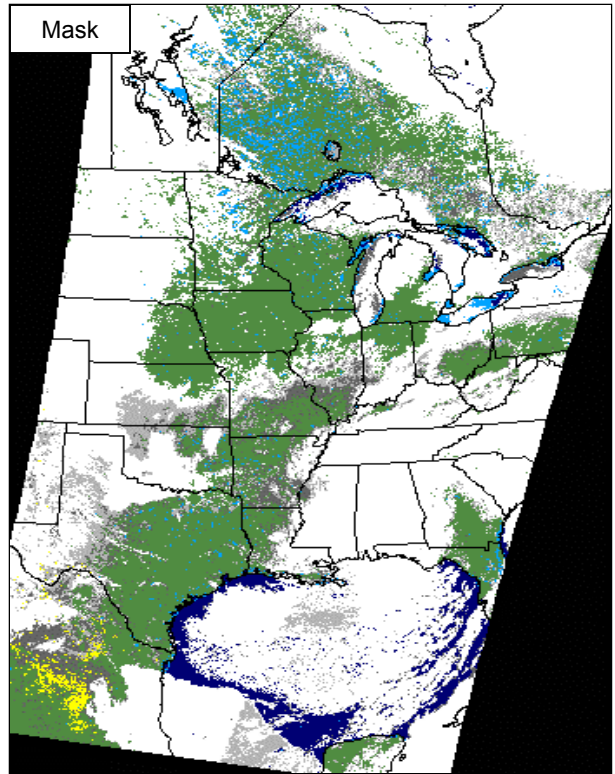
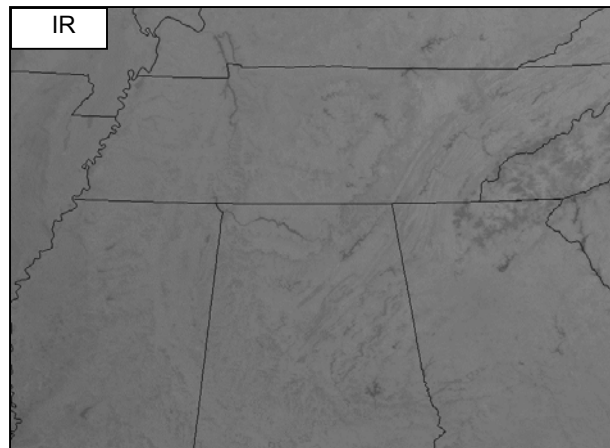


Figure 1. MODIS EOS land surface temperature (K), EOS cloud mask, and infrared image for 0735 UTC on 27th December 2003.

Figure 2. EOS MODIS cloud mask and MODIS false color composite for 1652 UTC on 15th February 2004.

2.2 NASA's SPoRT Program

In 2002, NASA established the SPoRT Center at Marshall Space Flight Center in Huntsville, Alabama as a vehicle to transition unique observing, modeling, and data assimilation capabilities (developed under the auspices of Earth Science Enterprise) to select NWS Forecast Offices (NWSFO's) and associated decision makers. This activity follows a "test bed" approach where unique data and analysis techniques are made available to NWS forecasters for real time assessment and use. The SPoRT program provides data, analysis and forecasting techniques, and training and participates with the NWS forecasters and decision makers in the assessment of new products and forecast capabilities. This interaction provides immediate feedback into the utility of the data in the operational environment. While this collaboration is facilitated by the collocation of the SPoRT Center and the Huntsville NWSFO, collaborations extend beyond the local office and include Birmingham (AL), Nashville (TN), Jackson (MS), Mobile (AL), and Great Falls (MT) forecast offices. This test bed approach has proven beneficial to the evaluation of the use of high-resolution satellite data from MODIS for a number of applications (Jedlovec et al. 2004; Lapenta et al. 2004).

3. METHODOLOGY

3.1 GHCC Cloud Mask Theory

An underlying principle of cloud detection using satellite imagery is that the difference between the emissivity of clouds at thermal wavelengths and at shortwave (reflective) wavelengths (such as 11.0 μm and 3.9 μm , respectively) varies from the same emissivity difference for the surface (land or ocean) and can be detected from channel brightness temperature (T_{bb}) differences. Emissivity varies with both wavelength and surface or cloud type, with the emissivity at the shortwave infrared wavelengths being smaller than at the longwave infrared wavelengths, resulting in lower emission at the shorter wavelengths. However, during the day reflected solar radiation makes the effective brightness temperatures (sum of emission and reflective components) at the shorter wavelengths larger than the brightness temperatures at the longer wavelengths even though the emissivity is less. Therefore for cloudy pixels, $T_{\text{bbLW}} - T_{\text{bbSW}}$ has a large negative value during the day, but at night, $T_{\text{bbLW}} - T_{\text{bbSW}}$ has a positive value (thick water clouds and fog) because there is no solar radiation, or a negative value (thin cirrus) even though the emissivity of ice clouds is about the same at the two wavelengths, much of the sensed energy comes from the earth's surface and the 3.9 μm channel's response to warm sub-pixel temperatures is greater than it is at 10.7 μm . Because the difference between shortwave and longwave emissivities is on average smaller for land and water than for clouds, clear pixels will have a small negative $T_{\text{bbLW}} - T_{\text{bbSW}}$ value during the day and a small negative or positive value at night. Thus, the transition from a

clear region to a cloudy region is manifested in the longwave minus shortwave brightness temperature difference image as a discontinuity. However, the fact that emissivities vary with cloud type and the effect of varying solar input at the surface or cloud top make this a challenging problem. Figure 3 shows a GOES-12 Imager nighttime 11 μm – 3.9 μm difference image (top) and the corresponding infrared image (bottom). Notice in the difference image that the lower, warmer water clouds have positive values, and the colder thinner clouds have negative values. Both the land and water have small values.

3.2 GHCC Cloud Mask Method

The GHCC cloud mask method (Haines et al. 2004) uses multispectral channel differences to contrast clear and cloudy regions. The GOES 11 μm and 3.9 μm channels are used to produce hourly difference images (longwave minus shortwave) for this purpose (see Figure 3). Both positive differences, which mainly occur at low sun angles and at night, and negative differences, that occur during all times, are preserved in the difference images. Two composite images are also created hourly, which represent the smallest negative and smallest positive difference image values (values closest to zero) from the preceding 20-day period. These composite images serve to provide spatially and temporally varying thresholds for the GHCC method. An additional 20-day composite image is generated for each time using the warmest longwave (11 μm) brightness temperature for each pixel from the 20-day period. These composite images are assumed to represent warm cloud-free thermal images, one for each time period.

The 20-day composite images used by the GHCC cloud mask are the unique aspect of the method and provide both spatially and temporally varying clear-sky values for comparison to the current infrared and difference imagery. By producing these composites, each pixel has the possibility of having a different threshold value from the next and therefore location, terrain, sun angle and snow cover are all taken into account. Figure 4 shows a daytime example of a negative difference 20-day composite image. Notice the large variation in the 11 μm – 3.9 μm differences across the region. The smaller differences (closest to zero) are over water, and the larger values are over land, particularly snow-covered land as in the Rocky Mountains. Without the composites, a single threshold value would be applied to the whole area, limiting the performance of the cloud mask.

The GHCC cloud detection method uses the above mentioned image products in a four-step cloud detection procedure for both GOES and MODIS imagery. This procedure is schematically described in Figure 5. The first test of the cloud mask algorithm subjects each pixel in the difference image (DI) to an adjacent pixel test. The variance between pixels DI(i) and DI(i-1) along the scan line in the difference image is computed. If the variance between these adjacent pixels is greater than the variance threshold value, a cloud (edge) is detected.

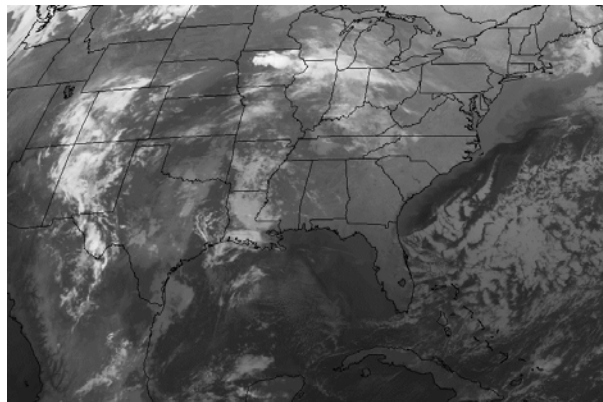
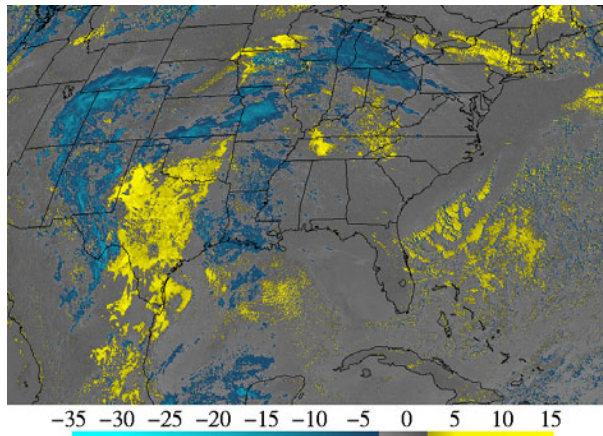


Figure 3. GOES-12 Imager nighttime $11\mu\text{m} - 3.9\mu\text{m}$ difference image and the corresponding infrared image.

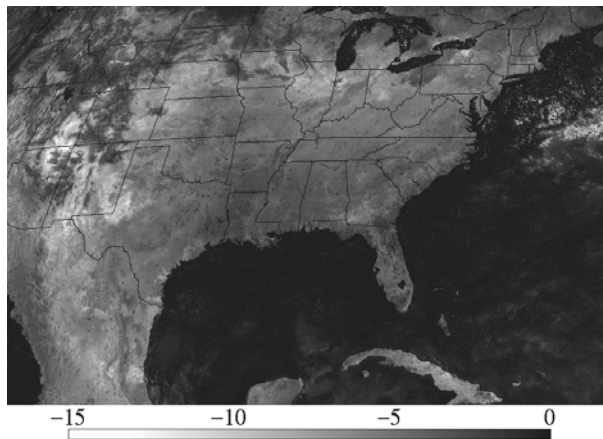


Figure 4. GOES daytime example of a negative difference 20-day composite image.

This procedure is more successful in identifying the edges of clouds during the day than at night. The second step attempts to fill-in between the cloud edges by analyzing the one-dimensional spatial variability of the pixels. To do this, two separate tests are used. The difference between $DI(i)$ and $DI(i-1)$ is calculated. For a cloud to be detected, this calculated difference value must be less than the cloudy threshold value if the preceding image location ($i-1$) was cloudy, or it must be either less than the negative of the clear threshold value or greater than two thirds of the clear threshold if the preceding image location was clear. In this way the spatial variability in the difference image corresponding to a cloud free surface versus a cloud is considered.

The next two steps in the GHCC method detect clouds in regions where the first two steps may fail by using a minimum difference test. The third step of the GHCC method utilizes the positive and negative composite images, which represent the smallest positive and negative difference image values, respectively, from the preceding 20-day period. The minimum difference test compares the current difference image value to these composite images. A pixel is deemed cloudy if the difference between $DI(i)$ and the smallest positive value is greater than the positive threshold value or if the difference between $DI(i)$ and the smallest negative value is less than the negative of the negative threshold value. The 20-day composite positive and negative difference images incorporate spatially varying information for nighttime and daytime cloud determinations separately.

The fourth and final test in the GHCC method involves using the longwave channel information. This IR threshold test uses an hourly 20-day composite of the warmest thermal infrared channel values at each pixel location. This product is essentially a "warm" cloud free thermal infrared image. A pixel in the observed infrared image is deemed cloudy if the infrared temperature is colder by at least the infrared threshold value than the warm thermal infrared channel composite temperature for that location and time period.

The GHCC MODIS cloud mask is generated using GOES composites (which are produced each hour using the 45 minute past the hour images) closest to the MODIS pass time. Both the GOES composites and the MODIS data are remapped into the same projection and resolution, although there are resolution differences between the original datasets. A problem not seen with the GOES data but is often seen in MODIS imagery, is sun glint in the ocean regions. Because of the sun glint problem, an adjustment was made to the MODIS cloud mask algorithm to allow for different threshold values for land and ocean during the daytime. Over the ocean the thresholds were changed so that fewer clouds were detected, mainly by the minimum negative difference test.

Figure 6 shows a daytime example of the MODIS cloud mask derived using the GHCC method. Notice how the mask is able to distinguish between snow and clouds particularly over Canada, and detects most of the clouds throughout the image. However, there is some over-determination of clouds in Southern Illinois.

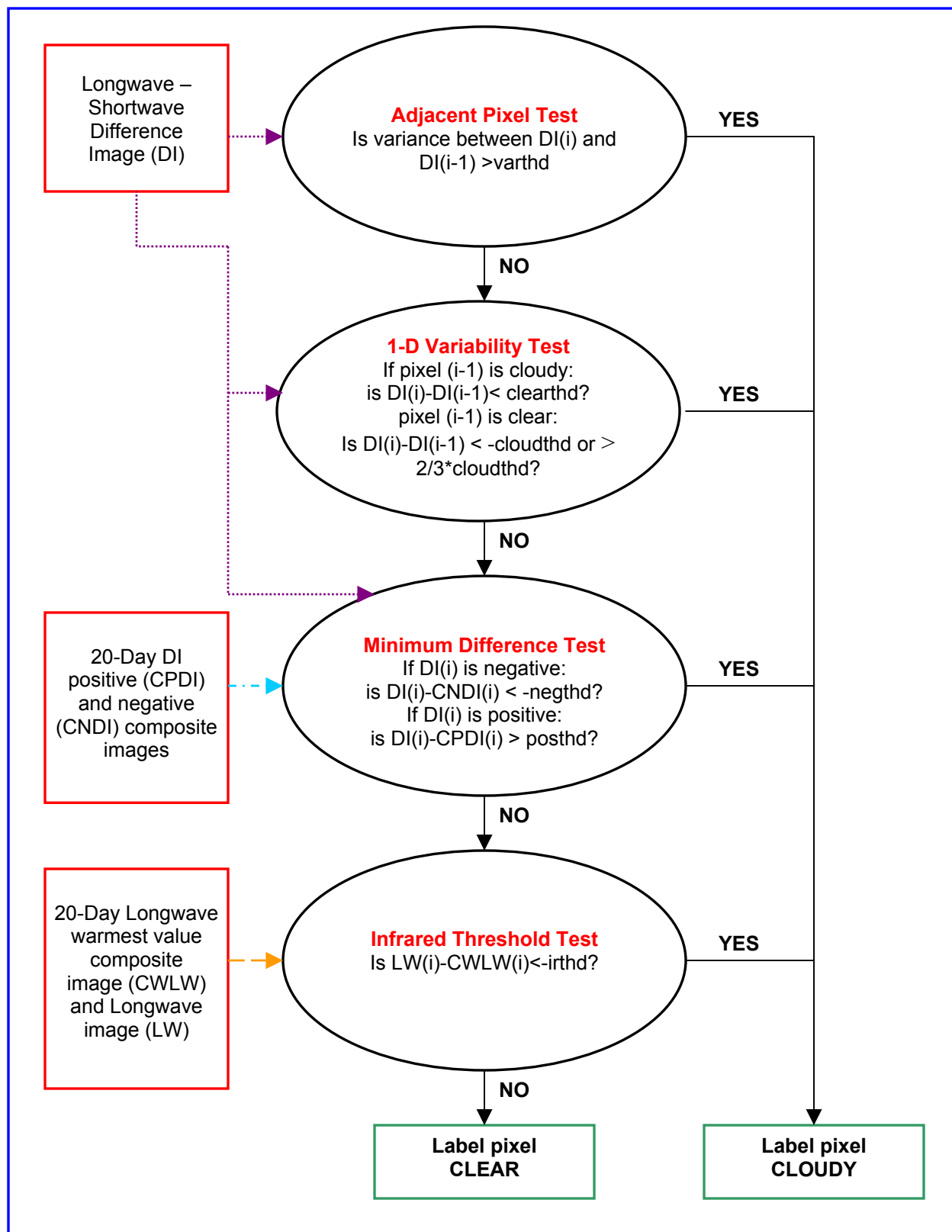


Figure 5. Flowchart of the GHCC cloud mask algorithm applied to both GOES and MODIS data

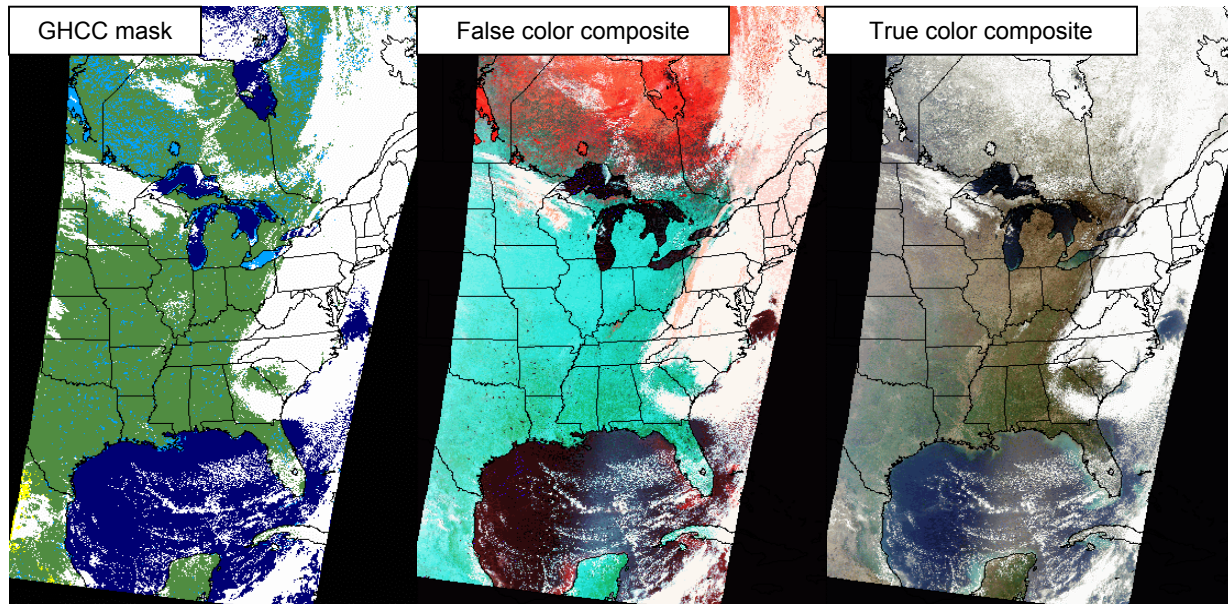


Figure 6. GHCC MODIS cloud mask, false color composite and true color composite from 1633 UTC 14 April 2004.

4. VALIDATION

4.1 Validation Method

Validation of any satellite-derived parameter including a cloud mask is difficult to achieve. Ground truth measurements are generally made at a single location (point measurement). Comparing a point to one or more pixels of a parameter derived from satellite data is often the only comparison method, but errors are inherent. The National Weather Service (NWS) Automated Surface Observing Systems (ASOS) present in many locations throughout the United States record cloud cover using a ceilometer that detects clouds only directly overhead and only up to an altitude of 12 000 feet (approximately 650 mb) (ASOS 2004). Because of the small observation area, the height limitation, and the fact that biases have been found between the automated method of determining cloud cover with these systems and manual observations (Perez et al. 2002), we decided that validating the GHCC MODIS cloud mask using ASOS data was not viable.

The cloud mask is validated using manual visual determination of the sky conditions using satellite imagery. By viewing the corresponding MODIS visible, color composites (daytime only), and infrared imagery at the same resolution, projection, viewing angle and coverage as the cloud mask, validation results were produced with a high level of confidence. Some problems do arise with this validation method, mainly human bias in the determination of cloud or no cloud within a given box, especially at night when only infrared imagery is available. To help overcome this problem, loops of GOES imagery were generated to view the movement of clouds with time, allowing for the

discrimination between snow and clouds and between warm clouds and the surface. Although looping the imagery resolved the cloud conditions for many of the times and locations, there were cases that the observer was unsure of, and these were labeled as uncertain.

The validation was performed by studying the cloud conditions within forty-two 40 km x 40 km boxes. The locations of these boxes are shown in Figure 7.

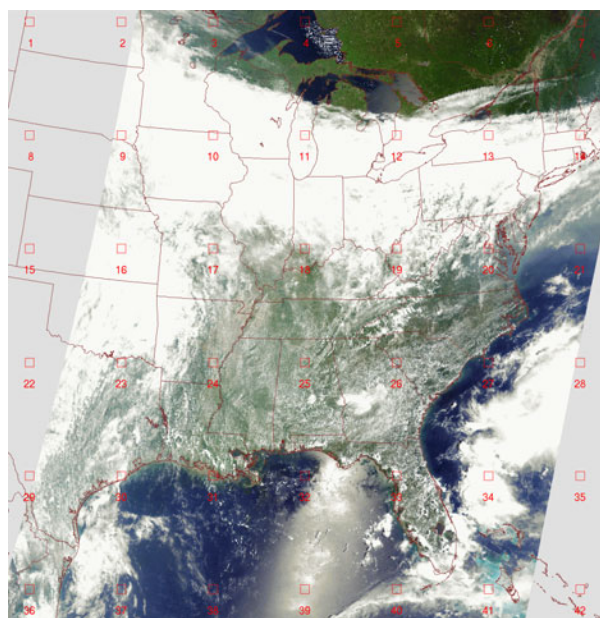


Figure 7. Location of the 42 boxes that were used to validate the GHCC MODIS cloud mask.

For each box the cloud condition was determined from the visible and/or infrared imagery as a percentage of coverage ranging from 0 – 100 % in increments of 10%. For the same boxes, the percent of cloud cover was estimated for the GHCC MODIS cloud mask and the EOS cloud mask produced in real time from the UW direct broadcast ground station, with separate determinations for the three cloud certainty levels of the EOS mask.

4.2 Validation Results

This paper includes validation results from two case studies using Terra data from this spring and early summer. The dates of the two periods are 4th – 19th April 2004 and 15th – 29th May 2004. Data from both the day and night passes were included. The results are separated into three groups: over-determination (cloud mask is at least 30% more than the observations), under-determination (cloud mask is at least 30% less than the observations), and correct (cloud mask is within 30% of the observations).

The Wisconsin/EOS results are presented in three levels: cloudy (UW-C), cloudy plus uncertain clear (UW-CU), and cloudy plus uncertain clear plus probably clear (UW-CUP). Figure 8 presents bar charts for the April (left column) and May (right column) case studies, with four charts for each case, separating land (day and night) and ocean (day and night). On each chart there are the GHCC results, and the three Wisconsin/EOS results, showing the percentage of the boxes that were determined to be correct (dark red), over-determining (yellow), and under-determining (purple).

The two case study periods described in this paper provide somewhat different cloud patterns and associated weather conditions, from spring to those of early summer, to test the performance of the MODIS cloud masks. The results presented in Figure 8 and described below provide insight into the preliminary performance of both the GHCC and the EOS MODIS cloud algorithms for regional applications over the Eastern U.S. No cloud algorithm will detect all the clouds on a regular basis and the utility of the cloud mask will vary with application. Some applications of the cloud mask can tolerate some missed clouds while others require a more conservative "over determined" mask for optimal results.

The four upper bar charts presented in Figure 8 show the daytime results for April and May for the land and ocean. The April case study daytime bar charts (218 comparison boxes for land and 111 for ocean over 16 days) show that the GHCC mask performs well, correctly identifying greater than 80% of the sky conditions (whether clear, cloudy or partly cloudy) at the validation locations over the land and ocean regions. The boxes incorrectly labeled indicate an over-determination of clouds at these points. The performance of the EOS cloud algorithm during the day is similar to that of the GHCC approach, although there is a tendency for reduced detection efficiency over the ocean with just over 20% of the points being over-determined. Considering the different levels of cloud

certainty contained in the EOS cloud mask; for all daytime conditions the percentage of over-determined pixels increases with the addition of a cloud mask (uncertainty) level, and the performance of the mask decreases. This implies that lowering the cloudy confidence level increases the number of incorrectly identified pixels. For the May daytime case study (298 boxes for land and 155 for ocean over 15 days), the overall performance of the two approaches changes, with the EOS mask correctly identifying on average about 90% of the sky conditions, with only small variations between land and ocean. In contrast, the GHCC mask does considerably worse, with the average number of boxes correctly identified falling below 70% over land, but still remaining greater than 80% over the ocean. An over-determination of low-level cumulus clouds by the GHCC algorithm is responsible for much of the poor performance over land during the May period.

The four lower bar charts in Figure 8 present the cloud mask performance results for the MODIS nighttime passes during the two case study periods. For the early April period (180 boxes over land and 109 boxes over ocean), the GHCC cloud detection algorithm performs well with about 86% of the sky conditions being correctly detected. This is slightly better than the daytime results for the same period. In contrast, the EOS mask shows a reduction in detection efficiency to below 70% for the period, due mainly to a significant over-determination of clouds over the ocean by the algorithm. In contrast with the daytime results over the land, there is an increase in the number of cloudy points that go undetected by the EOS algorithm. The EOS mask nighttime results for the late May case study period (283 boxes over land and 148 over ocean) are similar to those of the April period with reduced cloud detection efficiency over the ocean as a result of over-determination of clouds. The nighttime performance of the GHCC cloud mask algorithm for May is consistent with the April results, with just a slight reduction in performance between study periods. This is in contrast with the daytime results that showed a significant reduction in the performance over land. The presence of small-scale cumulus clouds forced by surface heating for the May case study days may explain the performance variations.

The statistics in Tables 1 and 2 provide overall results for the April and May periods, respectively, combining the land and ocean, and the day and night results. The numbers in these tables reflect the comparable performances of the GHCC and UW/EOS masks, showing the GHCC mask with a higher correct percentage of 84% than the EOS mask at 77% during the April period but lower during the May period (77% for GHCC compared to 82% for EOS), with most of the error in both cases occurring from over-determination. Notice that the values for the EOS/UW CU mask (cloudy plus uncertain clear) are very similar between the two periods, indicating the consistency of the EOS algorithm.

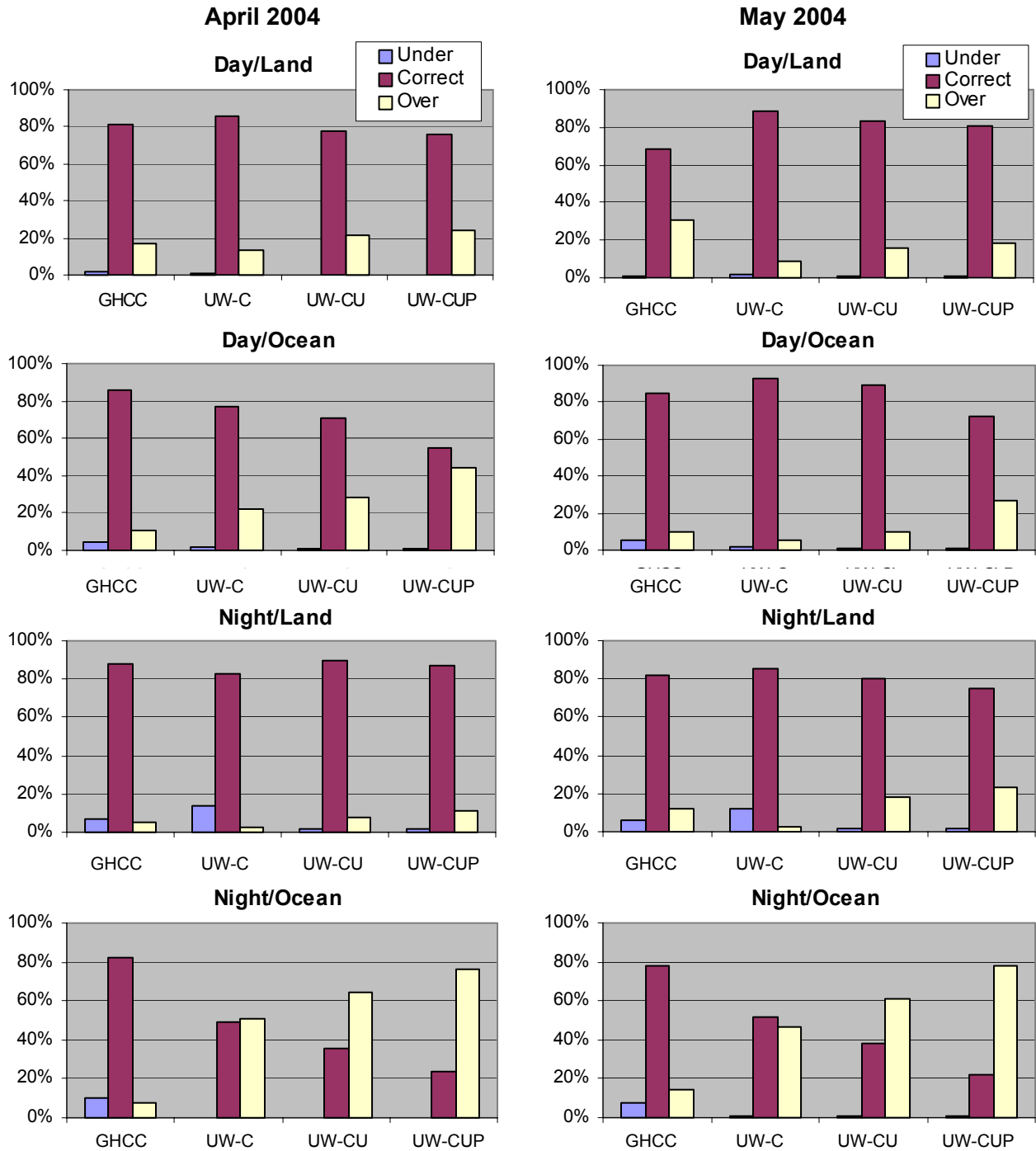


Figure 8. Charts presenting statistics of the April and May case studies of the GHCC MODIS cloud mask (GHCC), and the University of Wisconsin EOS cloud mask (UW-C (cloudy), UW-CU (cloudy plus uncertain clear), and UW-CUP (cloudy plus uncertain clear plus probably clear)). The charts show the percent of boxes that were correct (dark red), that over-determined (yellow), and that under-determined (purple), separated by land and ocean and also by day and night.

Table 1. Total statistics for the 4th – 19th April 2004 case study, generated from 618 samples.

	GHCC	UW-C	UW-CU	UW-CUP
Correct	84%	77%	73%	66%
Under	5%	4%	1%	1%
Over	11%	19%	26%	33%

Table 2. Total statistics for the 15th – 29th 2004 case study, generated from 884 samples.

	GHCC	UW-C	UW-CU	UW-CUP
Correct	77%	82%	74%	67%
Under	4%	5%	2%	1%
Over	19%	13%	24%	32%

Figures 9 and 10 show examples that illustrate two of the trends seen in the statistics. Figure 9 is a nighttime example (0339 UTC 15th April 2004) that highlights both the over-determination by the EOS mask over the ocean for all cloud certainty levels, and the high percentage of correctly determined pixels by the GHCC mask. Clouds that are readily apparent in the MODIS infrared image over the ocean are over-determined in the lower image corresponding to the EOS cloud mask. Some under-determination is also seen over the North Carolina and Virginia regions. The GHCC mask more accurately detects these clouds, although there may be slight under-determination off the west coast of Florida and over Michigan. Note that there is some uncertainty in the EOS cloud mask over most of the Gulf of Mexico (and limited regions over land), since much of the region is designated as uncertain clear (light gray) or probably clear (dark gray) in the mask data. While this may seem reasonable based on EOS detection approach, the product may limit coverage of derived surface and atmospheric parameters produced by the various science teams.

Figure 10 is a daytime example from May (1639 UTC 23rd May 2004) that highlights the poor performance of the GHCC mask over both land and ocean. Over the land, there is some over-determination, mainly caused by the filling in of pixels between scattered clouds. Over the ocean there is significant under-determination of clouds and a classification of the sun glint area as a cloudy region. The EOS mask also has problems in the sun glint region, although most of the sun glint area is labeled as probably clear (dark gray), there are linear "cloud" features in white that are not seen in the true color composite image (middle panel).

5. CONCLUSIONS

The MODIS cloud mask generated by the University of Wisconsin from their direct broadcast ground station using the EOS institutional algorithm has

been compared to a MODIS cloud mask generated from the same data stream at the Global Hydrology and Climate Center as part of NASA's Short term Prediction and Research Transition Center. The EOS approach uses numerous spectral tests and accompanying thresholds while the GHCC approach uses two spectral channels and limited spatial tests. The GHCC approach uses spatially and daily varying thresholds that are (currently) derived from composites of GOES imagery in channels similar to those used with MODIS. This threshold approach makes the GHCC algorithm somewhat unique and is responsible for its success over regional and local areas of interest.

The results presented here are from initial validation studies. The validation method involved determining the cloud amount within small boxes by human observations of satellite imagery. This validation method is subject to a margin of error because of the human input, however, it does take advantage of the knowledge and insight of a trained meteorologist with significant satellite remote sensing experience and a wealth of data from a variety of sources. The results from two case studies indicated that the EOS cloud mask generally performs well during the day, but has poor performance at night, particularly over the oceans. The GHCC mask was found to perform well during the April period, out-performing the UW mask at night and during the day over the ocean. However, the performance of the GHCC mask over land declined for the May case study, but was found to still be an improvement over the UW mask at night over the oceans.

6. FUTURE WORK

The results presented here represent just a few months of work on the adaptation of the GHCC GOES cloud mask algorithm to MODIS. There is still a great deal to be done that could improve the GHCC MODIS cloud mask. The GHCC cloud algorithm used in this research relied upon GOES-derived composites in channels similar to those of MODIS to provide initial threshold information for the GHCC spectral tests. This approach was used because of the availability of the GOES composites and the perceived difficulty in deriving the required composites from a 20-day period of MODIS data. Recent work has shown that composites can be generated from MODIS data, with clear-sky values for most of the region. The MODIS composites will be incorporated into the retrieval algorithm in the near future. The composites used in the algorithm provide initial threshold information for the spectral tests. The composite values are typically adjusted to provide some local tuning of the algorithm. No such tuning was done with the application to MODIS data. Day-night and land-ocean adjustments to the composites will be implemented in the near future. Threshold adjustments will also be made in sun glint regions. A more extensive semi-automatic validation study will be conducted with the updated algorithm in the near future.

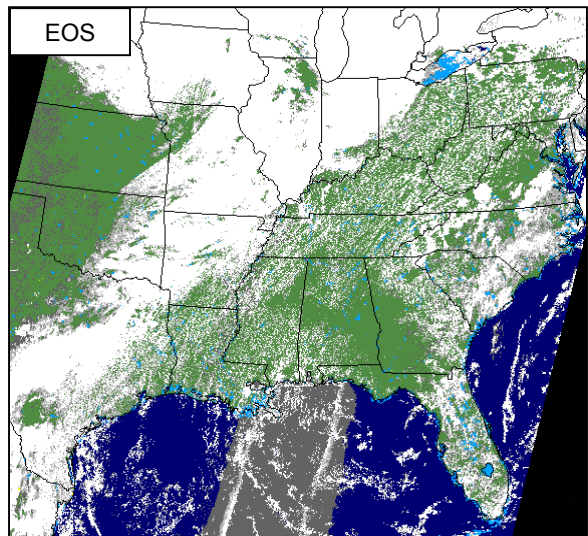
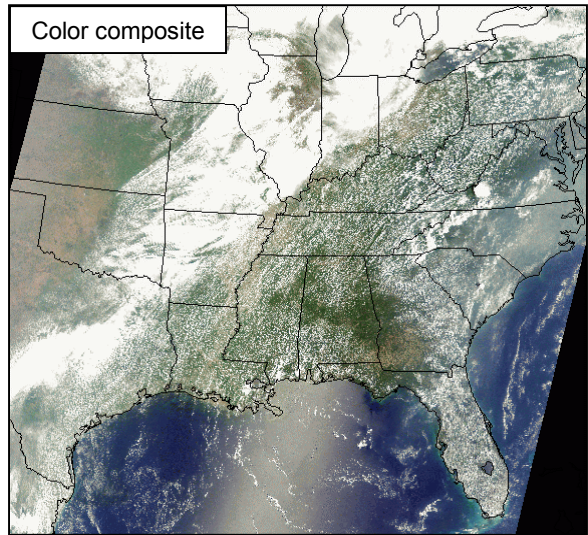
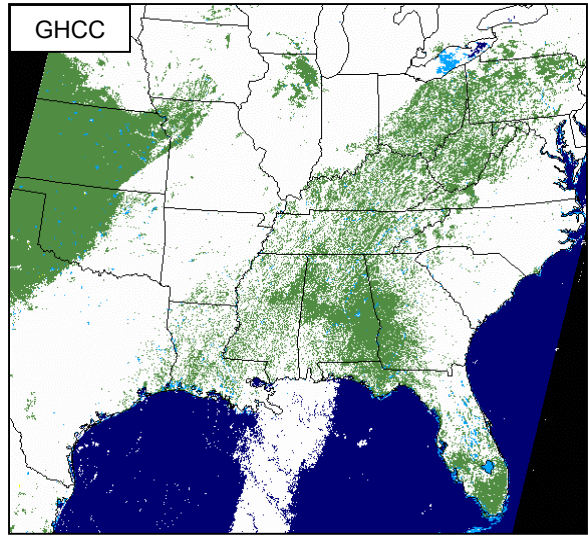
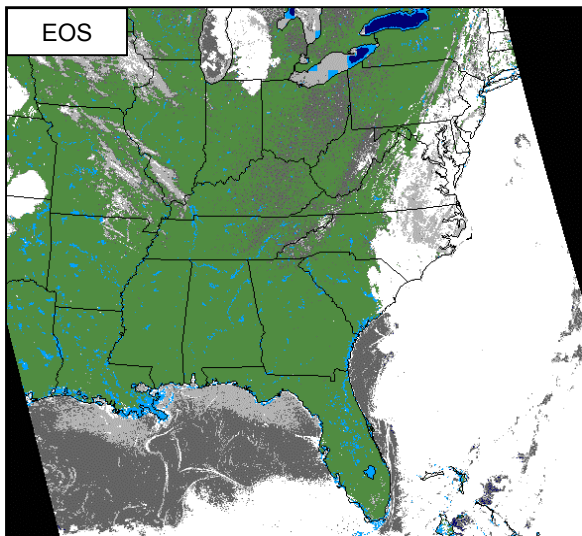
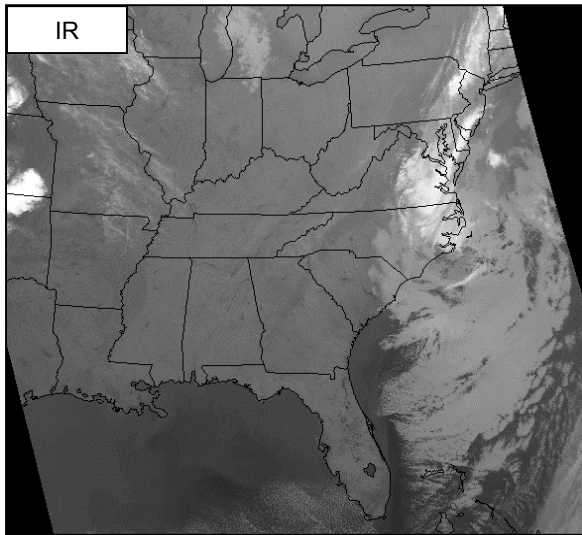
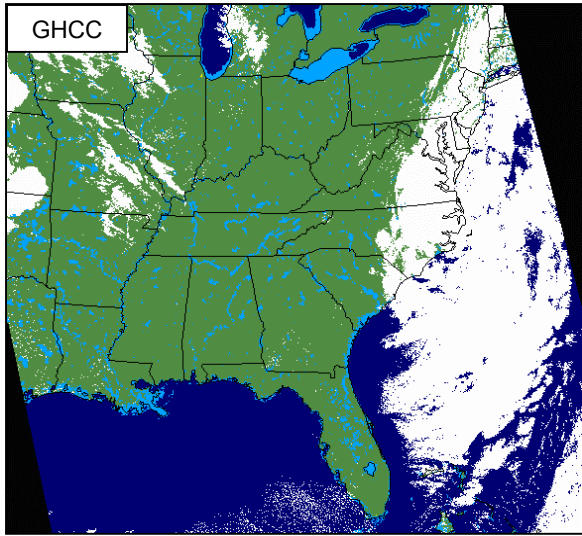


Figure 9. Nighttime example of the GHCC and EOS cloud mask with the corresponding IR image from 15th April 2004.

Figure 10. Daytime example of the GHCC and EOS cloud mask with the corresponding true color composite image from 23rd May 2004.

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