Are there clouds in the sky?

Reproducing the MODIS cloudmask using MODIS level 1 Radiance Data

EOSC 582 Final Project

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Clouds are generally cooler and more reflective than the earth's surface. The MODIS cloud mask uses this principle to test for cloud presence based on reflectances and brightness temperatures measured at different wavelengths of light by the Moderate Resolution Imaging Spectroradiometer, which orbits Earth on the Terra and Aqua Satellites (both built by NASA). This project aims to compare several bits of the MODIS 48-bit cloudmask with cloud determining tests performed on raw MODIS level 1 data. These tests were written using the Modis Algorithm Theoretical Basis Document as a guide (Ackerman et al, 2010), as well as Ackerman 1997, with the aim to examine how closely they reproduce the output of the final mask product. The tests of the MODIS mask are grouped into five functional groups, each using a combination of brightness temperature and reflectance ratio tests: Group 1. Detection of thick high clouds (using brightness temperature threshold tests) Group 2. Detection of thin clouds (brightness temperature difference tests) Group 3. detecting low clouds (reflectance thresholds and reflectance ratio tests) Group 4. detecting upper tropospheric thin clouds (reflectance threshold at 1.38 microns) Group 5. detecting cirrus clouds (brighness temperature difference tests)

I wrote tests for four bits of the mask (Bit 13 - Group 1, Bit 19 - Group 2, Bit 21 - Group 3, and Bit 24 - Group 2) and tested them on the skies over Great Britain using raw data from four different days. Bits 13, 19, and 24 use brightness temperature or brightness temperature difference, while Bit 21 uses a reflectance ratio. In analyzing the results, it is important to remember that each test is designed to look for different clouds under different conditions, and that a "clear sky" flag for a particular test means simply that a cloud was not found by that particular test (low clouds may not be detected by high cloud flags and vice versa). This is particularly important in the case of Group 1 and Group 3 tests, which complement each other - Group 1 tests are good at detecting high, thick clouds that exhibit a high thermal contrast with the surrounding area, while Group 3 tests can detect clouds that have a low thermal contrast using differences in reflectance ratios due to water vapour presence.

The final cloudmask is based on an amalgamation of the individual tests and is cloud-conservative - this is to say, in the case of borderline conditions it is more likely to assume cloud than clear sky.

The study area

I ran the tests on similar satellite passes on four separate days:

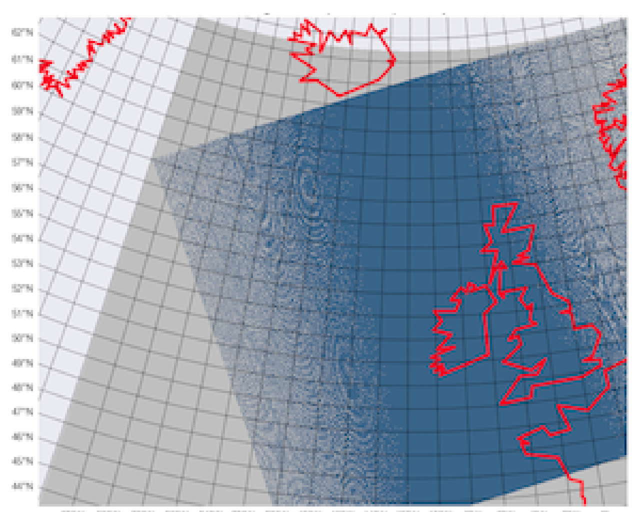
January 4, 2014 at 13:25

February 10, 2014 at 13:15

June 6, 2014, at 13:20

March 5, 2015, at 13:20

Though the passes differ slightly in spatial extent (according to time of satellite passing), all four cover Great Britain. The image below represents the spatial extent of one of the passes. For the cloudmask tests, I focused on analyzing the area around Great Britain, so I set the extent of the maps between 49 - 59 ° latitude and -11 - 3° longitude.



The spatial extent of the pass on June 6, 2014, at 13:20

Data products used

In this analysis, I used 3 different types of NASA data products. All 3 can be downloaded at https://ladsweb.nascom.nasa.gov/data/search.html (https://ladsweb.nascom.nasa.gov/data/search.html), under the Aqua MODIS Satellite heading. The products are as follows:

-Level 1B calibrated radiances (MYD021KM, Aqua Level 1 Product) - contains radiance data at different bands of the MODIS for a given pass (denoted by date and time recorded in filename). A reference table of band number correspondences to wavelength can be found here: (https://en.wikipedia.org/wiki/Moderate-Resolution_Imaging_Spectroradiometer (https://en.wikipedia.org/wiki/Moderate-Resolution_Imaging_Spectroradiometer))

-Geolocation (MYD03, Aqua Level 1 Product) - Contains georeferencing information for a given pass (denoted by date and time recorded in filename, which can be matched with other products for the same pass).

-MYD35_L2 (MODIS Level 2 Cloud Mask and Spectral Test Results, Aqua Atmosphere Level 2 Product) - Contains the results of the MODIS cloudmask.

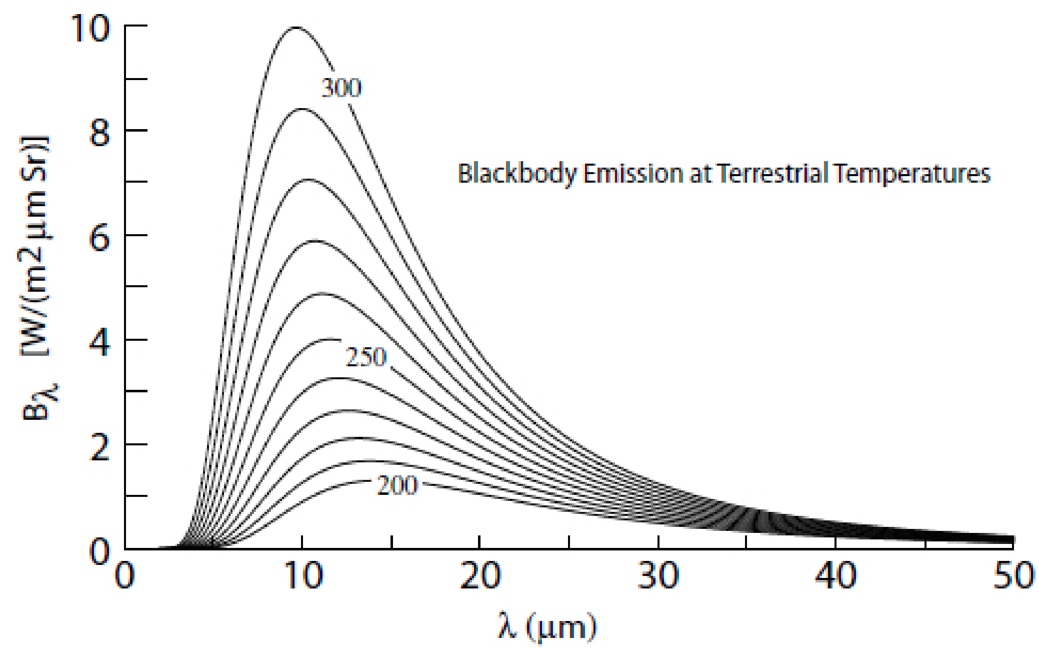
My aim in this analysis was to compare the MYD35_L2 cloudmask with the results of tests run on MYD021KM data. The visual comparison of both products (the MODIS cloudmask and my recreation of it) is enabled by plotting both using the same geolocation file.

The principle of brightness temperature

Many of the tests in the MODIS mask rely on calculations of the brightness temperature of observed surfaces. An object's brightness temperature at a given wavelength is a quantity related to its radiance at that wavelength by the Planck function. The Planck function gives radiance emitted by a body at a certain wavelength and temperature. The version used in this analysis is below:

$$\boxed{B_\lambda(T) = \frac{2hc^2}{\lambda^5\left(e^{hc/k_B\lambda T} - 1\right)}\ ,}$$

In this version of formula, λ is wavelength, c = 2.998 × 108 m s−1 is the speed of light, h = 6.626 × 10−34J s is Planck’s constant, kB = 1.381 × 10−23 J/K is Boltzmann’s constant, and T is temperature. The formula gives radiance in units of “power per unit constant, and T is temperature. The formula gives radiance in units of "power per unit area per unit solid angle per unit wavelength" (W m−2μm−1sr−1). This formula describes how a body's emitted radiance (B(T) at a given λ) changes with wavelength at a given temperature. The following graph of B(T) vs λ for different temperatures , taken from Petty 2011, was helpful to me in understanding this principle:



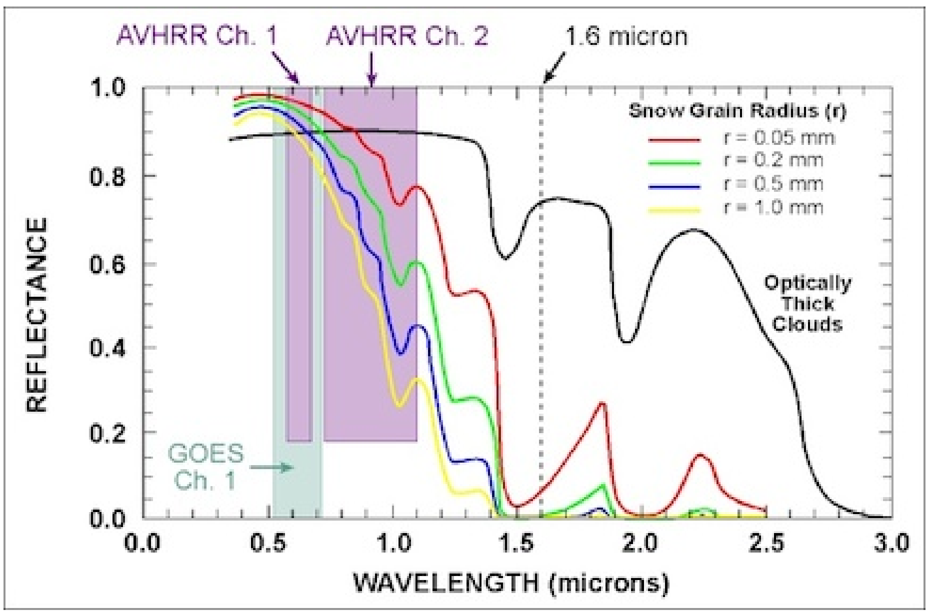
The MODIS sensor senses radiance at multiple wavelengths. If the radiance at a given wavelength is known, from the above function, a body's observed temperature at that wavelength can be found by inverting the Planck function and solving for temperature, as shown below (B -1 is the inverse of the Planck function, I(λ) is observed intensity).

$$T_B \equiv B_\lambda^{-1}(I_\lambda),$$

In the cloudmask, the MODIS sensor exploits the fact that different surfaces emit different intensities of radiations across wavelengths to distinguish between them. In some of the most simple tests, for example the test stored in Bit 13, it simply uses brightness temperature derived from radiation intensity at a given wavelength to discriminate between cold surfaces (which it designates as cloud) and warm ones (non-cloud). These tests are not applicable in all conditions - for example, it is difficult to distinguish between cloud and snow. More complex tests (eg Bits 19 and 24) utilize the idea that the presence of water vapour (cloud), changes radiation emitted differently at different wavelengths, and so use the difference between brightness temperatures at different wavelengths to predict the presence of clouds.

The principle of reflectance

When energy hits a surface, only three things can happen to it: It can be absorbed, it can be transmitted, or it can be reflected. Reflectance is the proportion of incident flux at a given wavelength which is reflected (as opposed to transmitted or absorbed) by a given surface. (Reflectance ranges from 0 to 1 and has no units.) Different surfaces have different reflectaces at different wavelengths, and if we have reflectance data for multiple wavelegths at our disposal, these differences can be used to identify corresponding surfaces. The following figure (produced by NOAA, see References for source) illustrates the difference between reflectances for various types of snow and thick cloud at different wavelengths:



Satellite channel wavelengths in microns and typical reflectance spectra for snow and clouds.

Several bits of the MODIS cloudmask exploit the different reflectances by different surface types at different wavelengths to distinguish between them. Of these, I attempted to recreate Bit 21, which uses the ratio of reflectance at .87 microns to the reflectance at .66 microns for cloud detection.

Bit 13: Brightness temperature at 11 microns

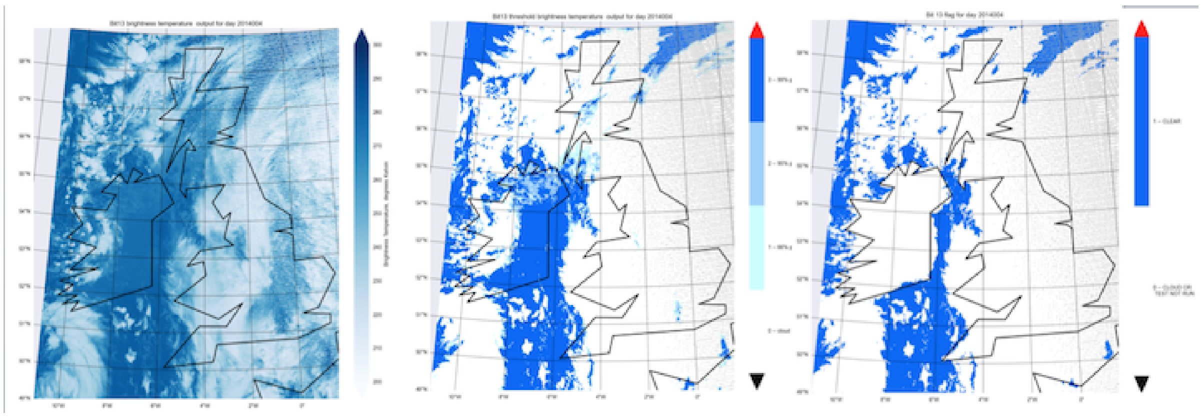
Bit 13 in the MODIS mask is a Group 1 test that uses brightness temperature at 11 microns (MODIS band 31, emissive channel 10) to determine the presence of thick high clouds (the colder the brightness temperature, the higher the chance of cloud presence). The test is difficult to use over land because surface emissivity varies considerably with soil and vegetation type, making it hard to discriminate colder background temperatures (eg. snow) from cloud. (According to Ackerman 1997, the test is most effective over ocean at night.) Ackerman uses the following thresholds: 267 K, 270 K and 273 K, with 270 K being the threshold value below which the pixel fails the clear-sky condition.

I recreated this test using a script that extracts radiance (W/m^2/micron/sr) at a wavelength of 11 microns for all pixels in a given MODIS level 1 file (filename designation MYD021), then finds brightness temperature from this radiance by solving the Planck function for brightness temperature using this radiance. (The Planck inversion functon was written by Phil Austin).

This script returns an array of brightness temperatures, which can be plotted using the MYD03 geolocation file. It is then possible to write a script that takes an array of brightness temperatures as an input and returns a probability of cloudiness based on the Ackerman thresholds as follows (BT = Brightness Temperature). There are 4 categories of probabilities, with 0 representing cloudy sky and 3 representing a 99% probability clear sky, as listed below:

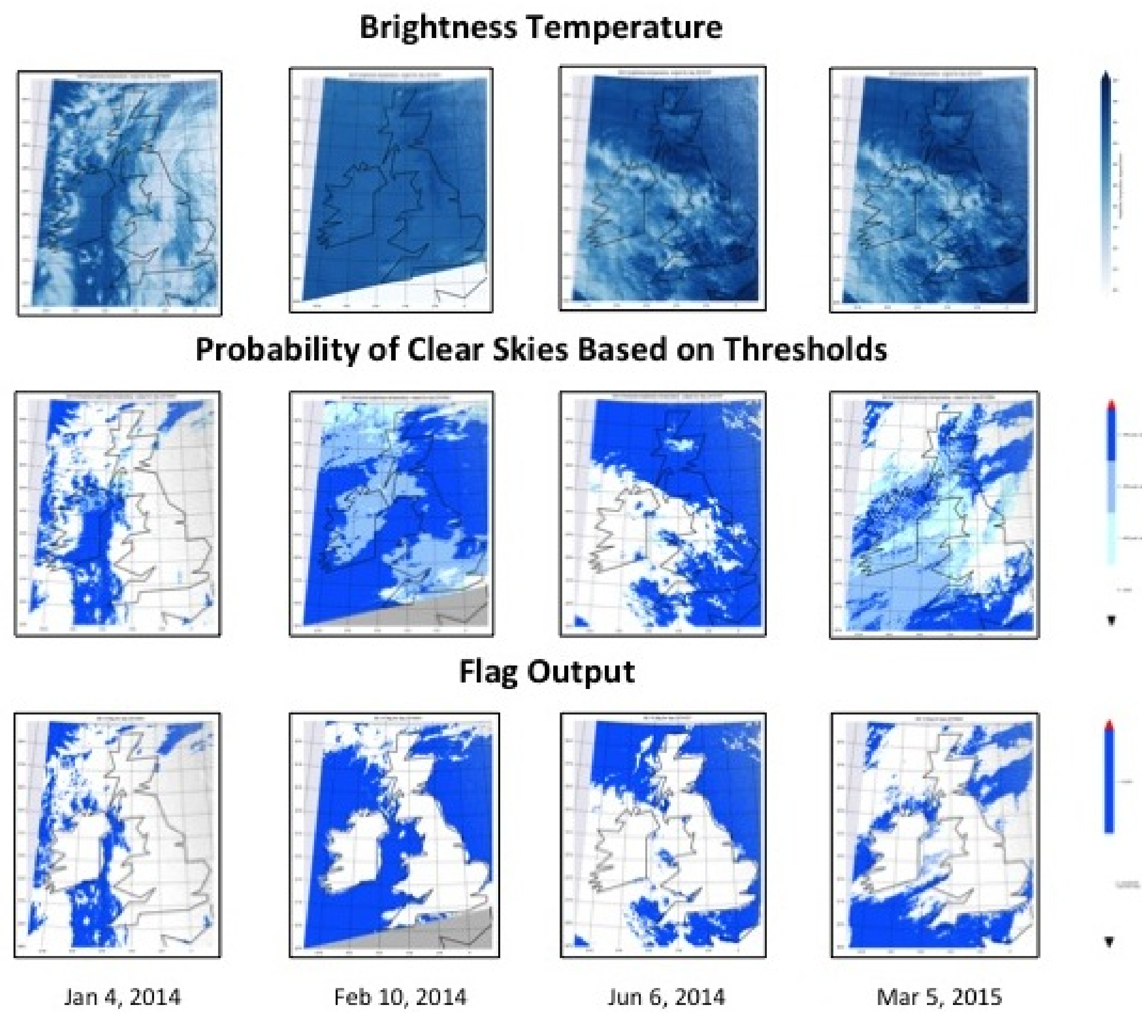
```
BT < 267..................... 0 - cloud (white on the map)
267 <= BT < 270 ..............1 - 66% probability clear
270 <= BT < 273 ..............2 - 95% probability clear
BT > 273......................3 - 99% probability clear (dar
k blue on the map)
```

I then compared the output of the threshold categorization with the bit 13 flag in the MODIS cloudmask. The MODIS cloudmask flag is binary, with 1 representing a clear sky and 0 representing the presence of cloud (in some cases, a 0 may indicate that the test was not run).
After this, all files (brightness temperature array, threshold array, and cloudmask array) can be reprojected (using P. Austin's reproject_numba code) and plotted with the help of the geolocation array) The following image represents a comparison of the scene January 4, 2014 at 13:25 with its threshold categorization and cloudmask.



A comparison of brightness temperatures, categorization results, and flag output for the January 4 scene

An overview of the same comparison for all 4 days can be seen below:



A comparison of brightness temperatures, categorization results, and flag output for all four scenes

Quantifying differences between my test and the MODIS mask: histograms

From this we can see that, as expected, the Bit 13 test does not appear to be run over land - the landmass always has a value of 0. Therefore, in order to quantify the difference between my categorization and the cloudmask, I need to compare the histogram of the 4 different cloud cover categories with the flag over open ocean. I did this over a small, randomly selected area with no land: 57-58 ° N, 8-10 ° W. Because the mapping files are reprojected, I had to round both the flag and threshold arrays to get discrete numbers in every reprojected cell for the purposes of the histogram. I created bar graph histograms of both the binary flag (values 0 and 1) and the category flags (0 1 2 3) by modifying P.Austin's histogram code. I also had the script print all found histogram values and proportions, which I am summarizing in the following tables:

January 4, 2014				
threshold	0	1	2	3
proportion of map	0.6228	0.093	0.077	0.2072
threshold group	___0/1___	___2/3___		
	0.7158	0.2842		
flag	0	1		
proportion of map	0.7524	0.2476		

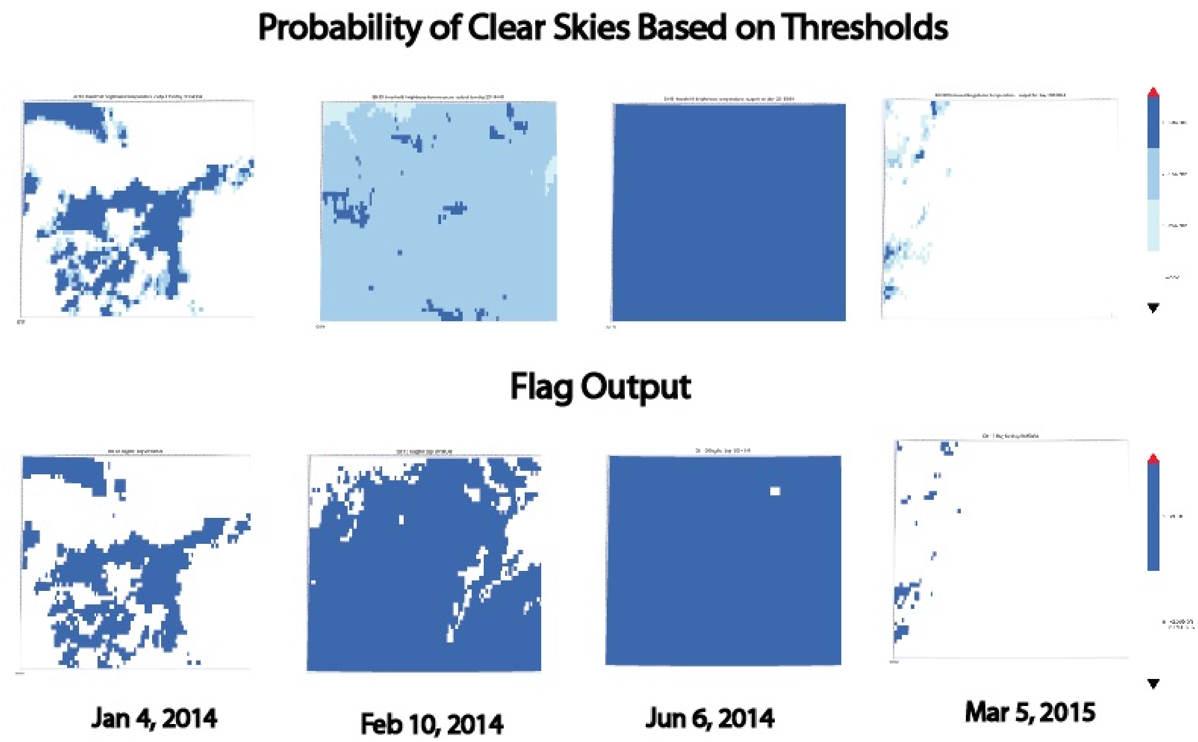
February 10, 2014				
threshold	0	1	2	3
proportion of map	0	0.0316	0.9222	0.0462
threshold group	___0/1___	___2/3___		
	0.0316	0.9684		
flag	0	1		
proportion of map	0.2074	0.7926		

June 6, 2014				
threshold	0	1	2	3
proportion of map	0	0.0154	0.0122	0.9724
threshold group	___0/1___	___2/3___		
	0.0154	0.9846		
flag	0	1		
proportion of map	0.0172	0.9828		

March 5, 2015				
threshold	0	1	2	3
proportion of map	0.9138	0.0464	0.035	0.0048
threshold group	___0/1___	___2/3___		
	0.9602	0.0398		
flag	0	1		
proportion of map	0.9696	0.0304		

A comparison of counts in brightness temperature threshold categories with counts of flag designations

To compare my threshold categories with the flag, I compared threshold categories 2 and 3 (>95% probability of clear sky) with the clear sky flag. From a first glance at the above table, we see that on January 4, June 6, and March 5, the threshold-category prediction of clear skies agrees relatively well with the clear-sky flag- on March 5 and June 6 the predictions are more or less identical (The biggest difference is on January 4, where the flag predicts clear skies for 24.7% of the studied area, while my categories predict clear skies for 28.4% of the studied area.) On February 10, however, the predictions differ considerably. To see why this is, I created maps of the threshold categories as well as the flag for just the histogrammed area (57-58 ° N, 8-10 ° W).



The same comparison on the visual map

When looking at these images, I noticed two features in the representation. First, the proportions listed in the histogram tables do not perfectly match the maps produced (This can be easily seen from Jun 6, where the map shows the full area as category 3, while the histogram shows a small amount of data in categories 1 and 2). This can be attributed to slightly different rounding scheme in each case - when reprojecting raw data onto a new grid, it's binned in each cell of the grid, and the raw data points binned into each cell are then averaged and then assigned a value. The category map seen above is produced from an already-binned brightness temperature map, while the histogram is produced by rebinning the category map and then rounding to produce integer values. This helps to account for the discrepancy between the two representations of the data.

The other interesting feature regards the difference between the cloudmask and my threshold categorization. The instance where my categorization differs most from the cloudmask (on February 10) is also the day with the largest proportion of the data in the intermediate threshold categories. On all other days, over 80% of the data can be binned into one of the extreme categories - 0 for cloud, or 3 for 99% clear. On February 10, 92.2% of the data is in category 2, meaning that it is closer to the cutoff boundary for the final cloudiness/clear sky categorization. In such cases, the NASA cloudmask algorithm uses other factors to help decide whether a pixel is cloudy or clear - for example, the presence of definitively cloudy pixels nearby (If a 'borderline clear' pixel is surrounded on all sides by 'definitively cloudy' pixels, it's very likely that the pixel is also cloudy). My algorithm does not do this, and so does not have extra information to help find clouds. Because the NASA cloudmask shows a larger proportion of cloud than my categorization, it is likely that these secondary tests were used.

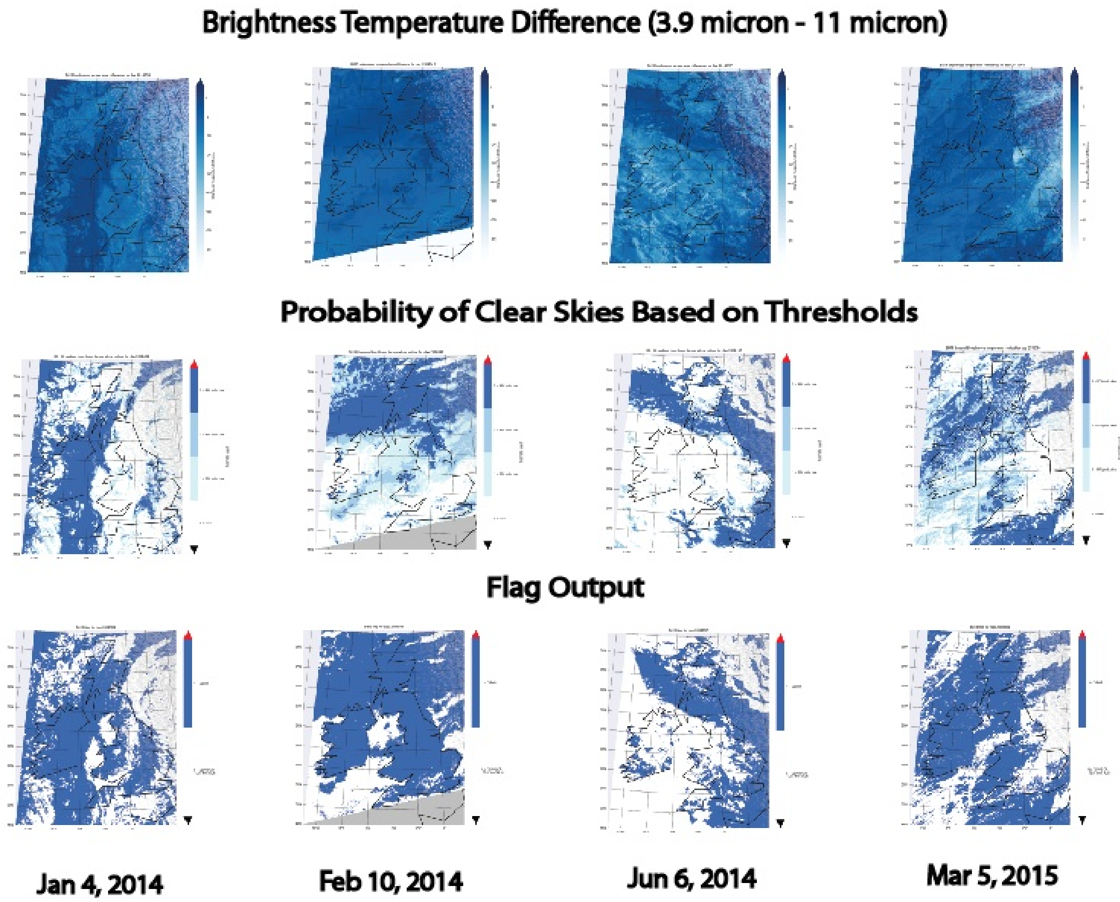
Bit 19: Difference between brightness temperatures at 11 and 3.9 microns

Bit 19 in the MODIS mask is a Group 2 test that uses the difference between the brightness temperature at 11 microns (MODIS band 31, emissive channel 10) and the brightness temperature at 3.9 microns (MODIS band 22, emissive channel 2) to determine the presence of low-level water clouds (in the presence of cloud water vapour, more solar energy is reflected at 3.9 microns than at 11 microns, creating the difference that the test relies on).

I recreated this test in a similar fashion as the test for bit 13, by using a script that extracts radiances (W/m^2/micron/sr) at wavelengths of 11 and 3.9 microns for all pixels in a given MODIS level 1 file (filename designation MYD021), then finds brightness temperatures from both radiances using the same Planck inversion function as above. The array of brightness temperatures at 3.9 microns is then subtracted from the array of brightness temperatures at 11 microns to create an array of differences (BTDIFF). Ackerman uses the following threshold categorizations for the bit 19 test:

```
BTDIFF < -10 ..................... 0 - cloud (white on the m
ap)
-10 <= BTDIFF < -8 ..............1 - 66% probability clear
-8 <= BTDIFF < -6 ..............2 - 95% probability clear
BTDIFF > -6......................3 - 99% probability clear
(dark blue on the map)
```

An overview figure of the three types of maps produced (brightness temperature difference, categorizations, and cloud flags) can be seen below:



A quick look at the result suggests that though the test was run over land, the flag output does not agree well with threshold categorization there. This is again likely due to the variability of the background emissivity of different land/vegetation types - the test's authors write that the thresholds of the bit 19 test are adjusted over different vegetation types (Ackerman 2010). However, without a land type map or an idea of the corresponding adjustment, the test does not appear to be very useful over land (this can be seen for example in the difference between the flag output and the difference map for February 10). Thus, I repeated the histogramming exercise for the same portion of the map (57-58 ° N, 8-10 ° W) over sea, to see how good the agreement was there. The result of the histogramming exercise can again be seen in the tables below:

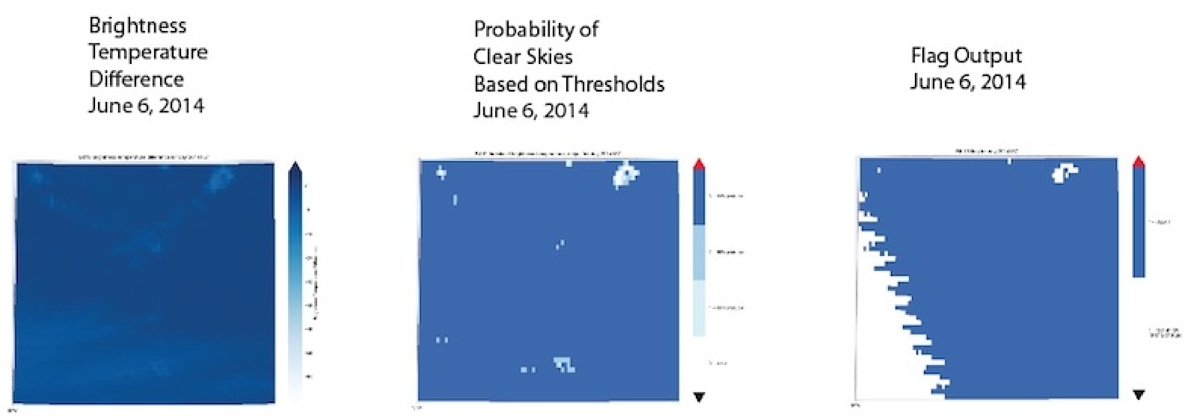
January 4, 2014				
threshold	0	1	2	3
proportion of map	0.3156	0.1698	0.1372	0.3774
threshold group	0/1	2/3		
proportion of map	0.4854	0.5146		
flag	0	1		
proportion of map	0.4826	0.5174		

February 10, 2014				
threshold	0	1	2	3
proportion of map	0.001	0.1008	0.4662	0.432
threshold group	0/1	2/3		
proportion of map	0.1018	0.8982		
flag	0	1		
proportion of map	0.128	0.872		

June 6, 2014				
threshold	0	1	2	3
proportion of map	0.0172	0.0156	0.0102	0.957
threshold group	0/1	2/3		
proportion of map	0.0328	0.9672		
flag	0	1		
proportion of map	0.1778	0.8222		

March 5, 2015				
threshold	0	1	2	3
proportion of map	0.6406	0.2492	0.1008	0.0094
threshold group	0/1	2/3		
proportion of map	0.8898	0.1102		
flag	0	1		
proportion of map	0.8936	0.1064		

Again grouping the threshold categories into 0/1 and 2/3 for comparison with the flag, we see very good agreement between the threshold groups and the flags on January 4, February 10, and March 5 (The predicted proportions of cloud cover by the two methods are within 3% of each other. On June 6, however, the threshold categorization predicts much more clear sky than the flag output does. I produced a closeup map of the 1x2 degree grid for this day to see why this might be the case:



Based on the 'unnatural' shape of the Flag-0 feature, I conclude that the test was simply not run in this area - furthermore, the shape suggests a defined boundary that my program may have reprojected and distorted. The cloud feature to the right of the boundary, in the upper right hand corner, appears to have been preserved (it appears both in the brightness temperature difference map and in the flag output map).

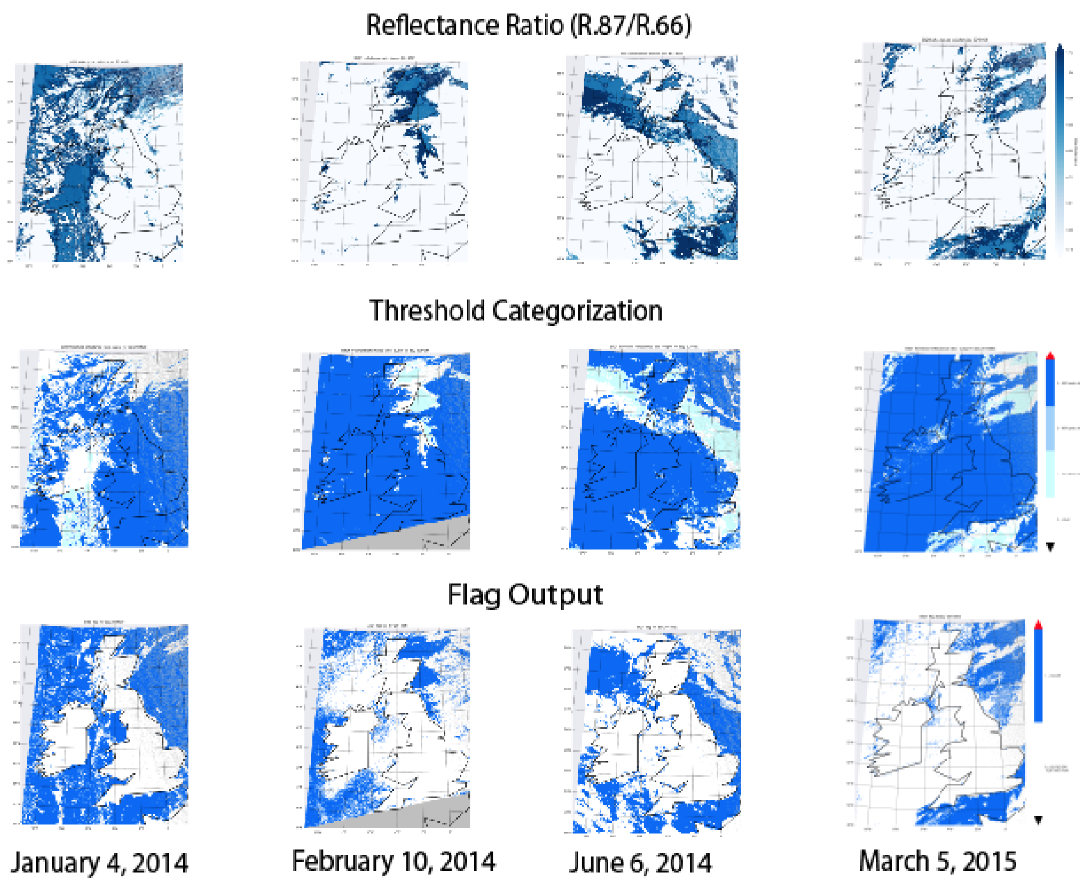
Bit 21: reflectance ratio

Bit 21 uses the ratio between the reflectance at .87 microns (MODIS band 13, emmissive channel 5) and 0.66 microns (MODIS band 16, emmissive channel 8) to determine the presence of clouds over water. The test utilizes the idea that the reflectances at these two wavelengths are similar when clouds are present in the scene but different over both water and vegetation. The test authors write that this ratio (R.87/R.66) should be less than

.75 over cloud-free ocean, greater than 1 over vegetation, and between .9 and 1.1 over cloud. In my reconstruction, I utilized the thresholds that the authors specify when running the test over water (RR signifies reflectance ratio):

```
RR > .95 ..................... 0 - cloud (white on the map)
.9 <= RR < .95 ..............1 - 66% probability clear
.85 <= RR < .9 ..............2 - 95% probability clear
RR < .85 ......................3 - 99% probability clear (da
rk blue on the map)
```

An overview figure of the three types of maps produced (brightness temperature difference, categorizations, and cloud flags) can be seen below:



From the result we see two things. First, as expected, the test is not run over land. The second is that the reflectance ratio gives precisely the opposite solution than the flag output - where the mask is flagged as cloud, my categorizations show clear sky, and vice versa. I believe this means that though I am extracting the correct data, I am not processing it correctly. Below is the code I used to extract and categorize the reflective data:

```
def bit21extract(cloud_mask,l1b_file):
  with h5py.File(l1b_file) as l1b_file, h5py.File(cloud_mas
k) as cloud_mask_h5:
    #band 13 is reflective channel 5
    index13=5
    band13=l1b_file['MODIS_SWATH_Type_L1B']['Data Fields']
['EV_1KM_RefSB'][index13,:,:]
    scale=l1b_file['MODIS_SWATH_Type_L1B']['Data Fields']['E
V_1KM_RefSB'].attrs['reflectance_scales'][index13]
    offset=l1b_file['MODIS_SWATH_Type_L1B']['Data Fields']
['EV_1KM_RefSB'].attrs['reflectance_offsets'][index13]
    band13=(band13 - offset)*scale
    #band 16 is reflective channel 8
    index16=8
    band16=l1b_file['MODIS_SWATH_Type_L1B']['Data Fields']
['EV_1KM_RefSB'][index16,:,:]
    scale=l1b_file['MODIS_SWATH_Type_L1B']['Data Fields']['E
V_1KM_RefSB'].attrs['reflectance_scales'][index16]
    offset=l1b_file['MODIS_SWATH_Type_L1B']['Data Fields']
['EV_1KM_RefSB'].attrs['reflectance_offsets'][index16]
    band16=(band16 - offset)*scale
    #getting appropriate bits from cloudmask
    cloud_mask_all=cloud_mask_h5['mod35']['Data Fields']['Cl
oud_Mask'][...]
    bit21_flag=bitmap.getbit(cloud_mask_all[2,:,:],5)
return band13, band16, bit21_flag

def b21rat(band16,band13):
    b21RATIO = band16/band13
return b21RATIO

def bit21threshold(b21RATIO):

    b21thres = np.copy(b21RATIO)
    b21thres[(b21RATIO > .95)] = 0
    b21thres[(b21RATIO >= .9) & (b21RATIO <.95 )] = 1
    b21thres[(b21RATIO >= .85) & (b21RATIO <.9)] =2
    b21thres[(b21RATIO <.85)] = 3
return b21thres
```

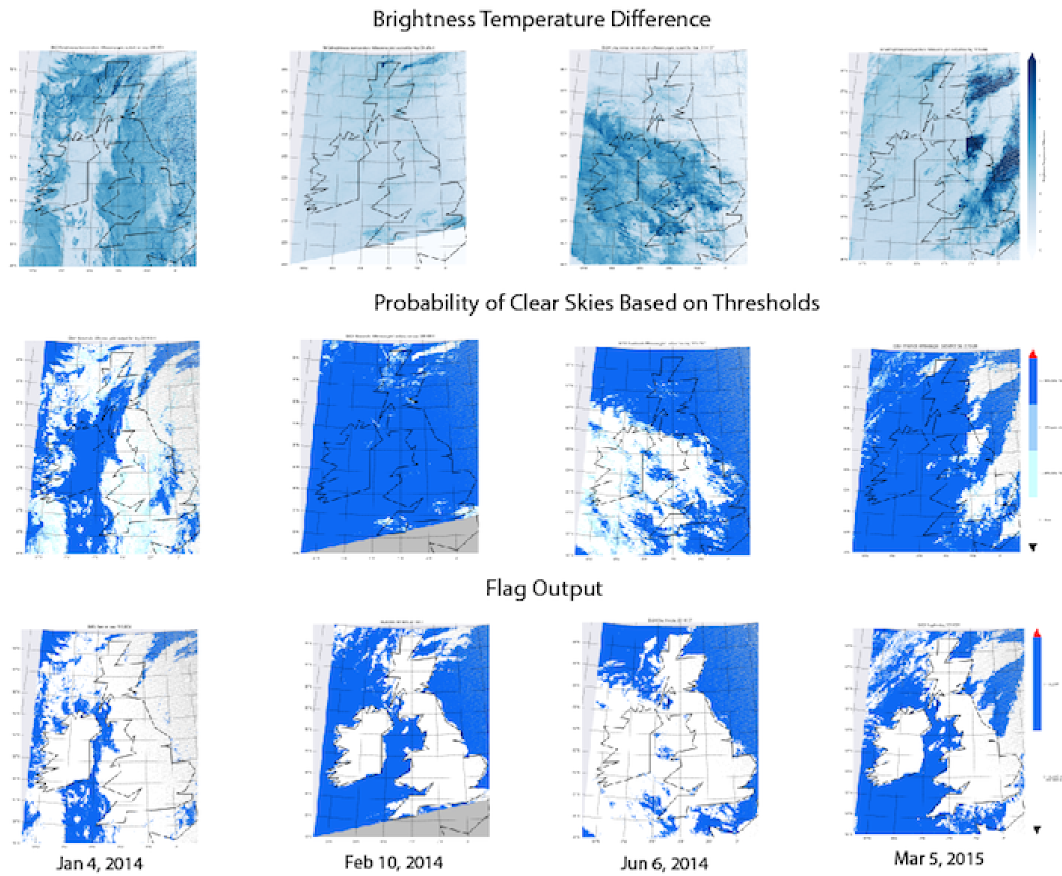
One possibility is that I am not correctly adjusting the band 13 and band 16 offsets. The other possibility is that the ratio thresholds for the mask need to be adjusted in a different way. I was not able to find this information in any of the Ackerman MODIS documentation, so I would like to seek advice about it and adjust the results after I find a way forward.

Bit 24: Difference between brightness temperatures at 11 and 8.6 microns

Similarly to Bit 19, Bit 24 uses the difference between the brightness temperature derived from radiance at 11 microns (MODIS band 31, emissive channel 10) and the brightness temperature derived from radiance at 8.6 microns (MODIS band 29, emissive channel 8) to determine the presence of clouds based on the different water vapour absorption at different wavelengths and resulting difference in brightness temperatures. I again used the thresholds listed in Ackerman 2010 for the test (BTDIFF in this case represents BT8.6 - BT11):

```
BTDIFF > 0 ..................... 0 - cloud (white on the ma
p)
-.5  <= BTDIFF < 0 ..............1 - 66% probability clear
-1 <= BTDIFF < -.5 ..............2 - 95% probability clear
BTDIFF < -1......................3 - 99% probability clear
(dark blue on the map)
```

An overview figure of the three types of maps produced (brightness temperature difference, categorizations, and cloud flags) can be seen below. (Note: In the top row, large positive values (which indicate the presence of cloud) are darker blue, which contrasts with the designation for the flag maps and categorization maps, where white is cloud).



From the above maps we can see that the cloud detection tests are not run over land; this is because land surface emmittance by different vegetation types at 8.6 microns is quite variable. We again examine the effectiveness of the test over a water portion (57-58 ° N, 8-10 ° W) using histograms:

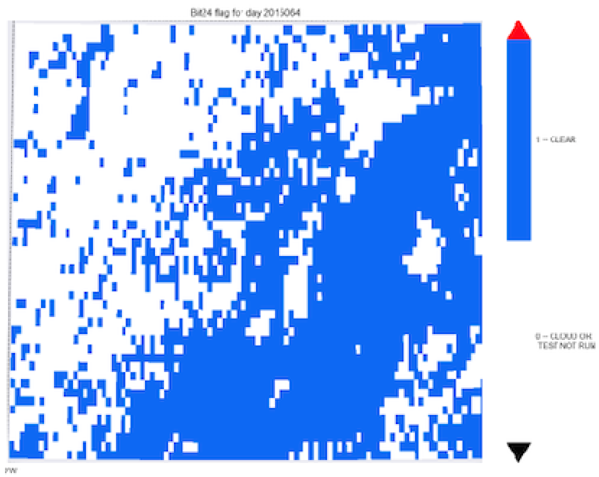
January 4, 2014				
threshold	0	1	2	3
proportion of map	0.3856	0.181	0.128	0.3054
threshold group	___0/1___	___2/3___		
proportion of map	0.5666	0.4334		
flag	0	1		
proportion of map	0.749	0.251		

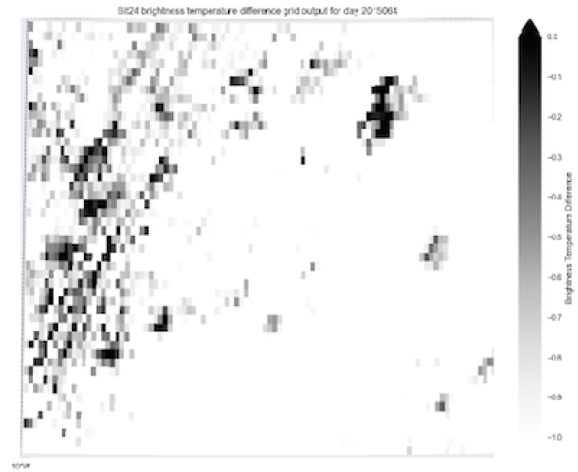
February 10, 2014				
threshold	0	1	2	3
proportion of map	0	0	0.0284	0.9716
threshold group	___0/1___	___2/3___		
proportion of map	0	1		
flag	0	1		
proportion of map	0.0934	0.9066		

June 6, 2014				
threshold	0	1	2	3
proportion of map	0	0.0124	0.014	0.9736
threshold group	___0/1___	___2/3___		
proportion of map	0.0124	0.9876		
flag	0	1		
proportion of map	0.0976	0.9024		

March 5, 2015				
threshold	0	1	2	3
proportion of map	0.006	0.0402	0.1814	0.7724
threshold group	___0/1___	___2/3___		
proportion of map	0.0462	0.9538		
flag	0	1		
proportion of map	0.5404	0.4596		

From this we see that my threshold categorization significantly underestimates cloud proportion compared to the flag designation for all four scenes. To see why this might be, looked at a close-up of one particular scene (March 5, 2015), comparing the brightness temperature difference at a fine scale (-1K to 0K) with the flag designation.





When we compare these images, it becomes apparent that we cannot attribute the larger proportion of cloud cover in the flagged image simply to the effect of adjacent pixels (the effect we considered in the bit 13 test, where cloudy 'neighbour pixels' seemed to make a pixel more likely to be cloudy). The thresholds listed in Ackerman categorize a pixel as definitively cloudy if the BTDIFF is positive - on the right hand side of the image we see that it is rarely the case for a pixel to have a positive BTDIFF, and that even pixels with BTDIFF values very slightly above -1 seem to be classified as cloudy. This suggests that in classifying these pixels, the algorithm may have shifted classification thresholds down from the values listed by Ackerman 2010 - even pixels with BTDIFF values close to -1 may have been classified as cloudy.

Summary

In this exercise, I aimed to reconstruct 4 elements of the MODIS cloudmask from first principles. I succeeded in doing so with relative accuracy for two of them: Bit 13 and Bit 19, where differences between the cloudmask and my created threshold categorization could be attributed to better discrimination by the cloudmask in the intermediate classification categories. In Bit 24, the cloudmask reports significantly more clouds than my tests, and a closer comparison suggests that the cloudmask's brightness temperature difference classification thresholds appear to be lower than in my reconstruction. In Bit 21, I was able to reconstruct the shape of clouds observed by the cloudmask, but my categorizations for the cloud categories were exactly opposite to those seen in the mask, suggesting that I am missing a processing step in my analysis.

References

In creating these reconstructions, I relied on data description and threshold categorizations presented in two publications:

Ackerman et al. "Discriminating Clear-sky from Clouds with MODIS" (Journal of Geophysical Research, submitted 1997)

Ackerman el al. "Discriminating Clear-sky from Clouds with MODIS: Algorithm Theoretical Basis Document (MOD 35)" October 2010

Explanations of the theory of reflectance and brightness temperature are from Grant W. Petty's "A first course in atmospheric radiation" (2010), and the equations and graphs from the brightness temperature section are also from this book.

The graph illustrating reflectances from different surfaces at different wavelengths is from the website of NOAA's National Operational Hydrographic Remote Sensing Center, found here: http://www.nohrsc.noaa.gov/technology/avhrr3a/avhrr3a.html (http://www.nohrsc.noaa.gov/technology/avhrr3a/avhrr3a.html)