Estimation of Gas Flaring Volumes Using NASA MODIS Fire Detection Products

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1. BACKGROUND

To date there has not been a satellite sensor optimized for the detection of gas flares and estimation of flared gas volume. For the past five years NGDC has been conducting research on the estimation of gas flaring volumes from DMSP nighttime lights data. The DMSP estimated gas flaring volumes indicate that global gas flaring has declined by 19% since 2005, led by gas flaring reductions in Russia and Nigeria, the two countries with the highest gas flaring levels. Based on reported crude oil production, flaring efficiency of both Russia and Nigeria improved from 2005 to 2008. This suggests that the reductions in gas flaring in these two countries are the result of either improved utilization of the gas, reinjection, or direct venting of gas into the atmosphere, although the effect of uncertainties in the satellite data cannot be ruled out. In this study we have investigated the use of NASA MODIS (Moderate Resolution Imaging Spectrometer) fire detection data to validate the gas flaring trends derived from DMSP.

In reviewing their experience in estimating gas flaring volumes with DMSP data Elvidge et al. (2009) noted several shortcomings : 1) gas flares are so bright that they often saturate the DMSP visible band, 2) gas flares can only be detected at night and cannot detect flares in mid-to-high latitudes during the summer due to solar contamination, 3) there is no on-board calibration for the DMSP visible band, making it difficult to estimate the total radiative output from gas flares, 4) it is impossible to identify gas flares inside of lit urban centers and at more remote gas flares lighting from the facility is included in the DMSP signal, and 5) the low light imaging data may be subject to environmental effects that are difficult to account for (such as the effect of varying land surface properties.).

To this list one more shortcoming should be noted. The current intercalibration between the satellite years of the DMSP products relies on the assumption that electric powered lighting on the island of Sicily has changed very little over the span of the DMSP archive. The Sicily site was selected as the best available after an exhaustive review of the stability of lighting in various regions. However, the possibility that the DMSP derived trends in gas flaring volumes are influenced by unrecognized changes in the lighting of Sicily cannot be entirely discounted. NGDC is developing an intercalibration for the DMSP archive based on the digital values recorded from moonlit desert surfaces.

These are all areas where NASA MODIS data may offer some advantage over DMSP for the estimation of gas flaring volumes:

1) The MODIS fire detection algorithm is based on data values from two thermal bands and has been designed to minimize false detections.

2) MODIS data are radiometrically calibrated and tends not to saturate when fires are observed, allowing for the calculation of brightness temperatures for fires and flares.
3) MODIS has dedicated fire bands which can distinguish gas flares from anthropogenic lighting (*i.e.* cities) that are not resolved in the DMSP data.
4) With MODIS data thermal anomalies can be detected day or night with no seasonal restrictions (other than cloud cover).
5) MODIS fire detections are not affected by lunar conditions or solar contamination, which reduce the number of usable observations in DMSP data.
6) NASA collects both daytime and nighttime data from two satellites (TERRA and AQUA), making it possible to observe gas flares at four different times during the day (morning, afternoon, mid-evening, and after midnight).
7) It is possible that flaring could be manipulated to avoid detection by the DMSP, which has an overpass time of approximately 19:30 local time. This would be significantly more difficult with the four overpasses per day of MODIS (i.e. Terra and Aqua, each with a morning and night overpass).
8) MODIS collects data at somewhat higher spatial resolution than DMSP (1 km versus 2.7 km).

2. THE MODIS FIRE PRODUCT (MOD14)

MODIS collects earth observation imagery in thirty-six spectral bands (Table 1). Thermal bands 21 and 22 (at 3.9 micrometers (um)) are particularly responsive to the presence of combustion sources (hot spots, or fires). The standard MODIS fire detection algorithms compares the brightness temperature in Bands 21 and 22 with that observed in Band 31, which is at a longer thermal wavelength (11 um) having little or no sensitivity to fires. This is shown graphically in Figure 1. The MODIS fire products (aka MOD14) are processed for each five minute granule of the MODIS orbit segments that include land. These are available from the USGS, which operates the land archive for NASA sensors. The fire detection algorithm is only run on land areas. The output includes a bitmap indicating the locations of fires, water, clouds and land (see example in Figure 2). An ancillary list of Fire Radiative Power estimates is included for each of the detected fires.

Documentation on the MOD14 products is available at: https://lpdaac.usgs.gov/lpdaac/products/modis_products_table/thermal_anomalies_fire/5_min_l2_swath_1km/v5/terra.

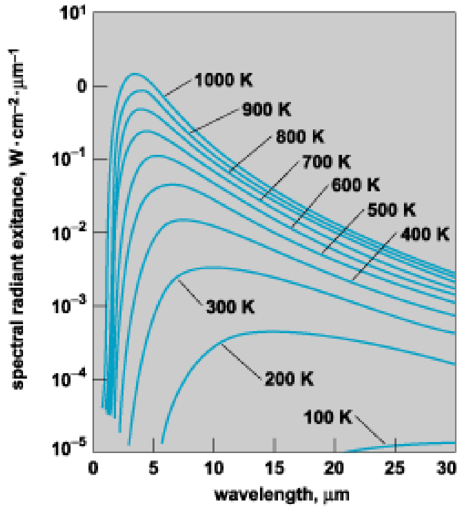

Figure 1. As an object heats up the quantity of radiation emitted increases and shifts to shorter wavelengths.

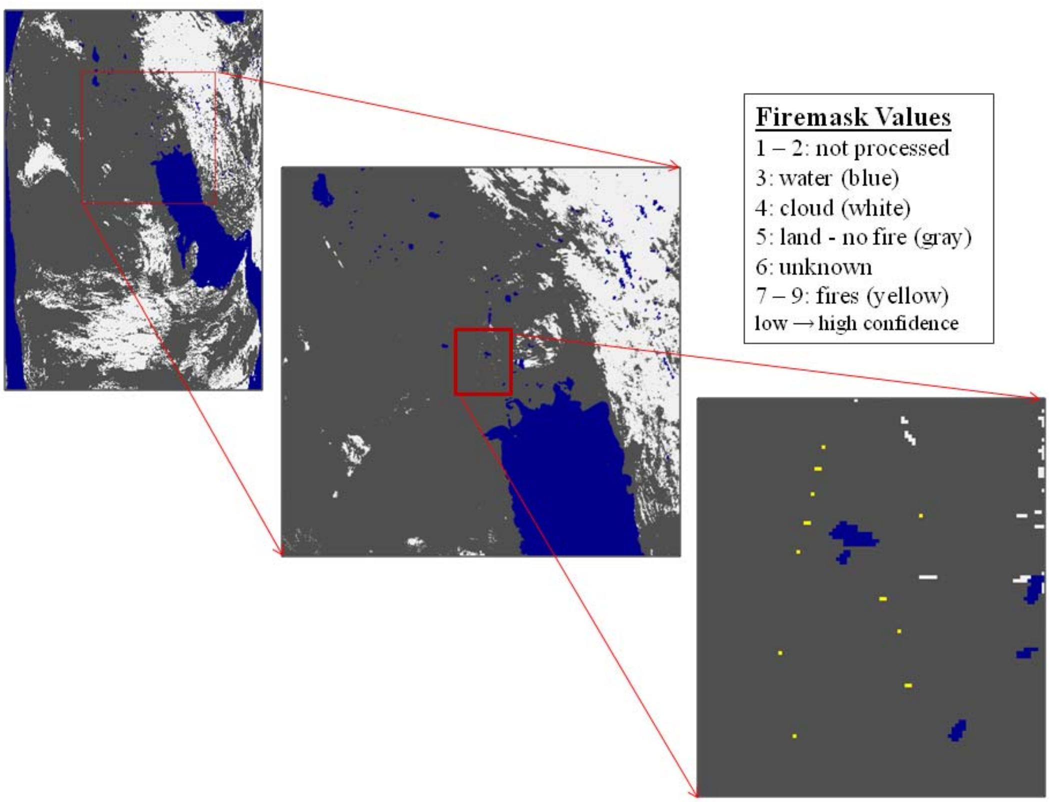

Figure 2. The MOD14 file covering the Persia Gulf and Arabian Peninsula from January 13, 2009 (granule MYD14.A2009013.1010.005.2009014064727.hdf). Land with no fire detection is gray, clouds over land are white, water is blue, and fire detections are red.

Table 1
MODIS Spectral Bands

Primary Use	Band	Bandwidth	Spectral Radiance
Land/Cloud/Aerosols Boundaries	1	620-670 nm	21.8 W
	2	841-876 nm	24.7 W
Land/Cloud/Aerosols Properties	3	459-479 nm	35.3 W
	4	545-565 nm	29.0 W
	5	1230-1250 nm	5.4 W
	6	1628-1652 nm	7.3 W
	7	2105-2155 nm	1.0 W
Ocean Color Phytoplankton Biogeochemistry	8	405-420 nm	44.9 W
	9	438-448 nm	41.9 W
	10	483-493 nm	32.1 W
	11	526-536 nm	27.9 W
	12	546-556 nm	21.0 W
	13	662-672 nm	9.5 W
	14	673-683 nm	8.7 W
	15	743-753 nm	10.2 W
	16	862-877 nm	6.2 W
Atmospheric Water Vapor	17	890-920 nm	10.0 W
	18	931-941 nm	3.6 W
	19	915-965 nm	15.0 W
Surface/Cloud Temperature	20	3.660-3.840 µm	0.45 W (300 K)[1]
	21	3.929-3.989 µm	2.38 W (335 K)[1]
	22	3.929-3.989 µm	0.67 W (300 K)[1]
	23	4.020-4.080 µm	0.79 W (300 K)[1]
Atmospheric Temperature	24	4.433-4.498 µm	0.17 W (250 K)[1]
	25	4.482-4.549 µm	0.59 W (275 K)[1]
Cirrus Clouds Water Vapor	26	1.360-1.390 µm	6.0 W
	27	6.535-6.895 µm	1.16 W (240 K)[1]
	28	7.175-7.475 µm	2.18 W (250 K)[1]
Cloud Properties	29	8.400-8.700 µm	9.58 W (300 K)[1]
Ozone	30	9.580-9.880 µm	3.69 W (250 K)[1]
Surface/Cloud Temperature	31	10.780-11.280 µm	9.55 W (300 K)[1]
	32	11.770-12.270 µm	8.94 W (300 K)[1]
Cloud Top Attitude	33	13.185-13.485 µm	4.52 W (260 K)[1]
	34	13.485-13.785 µm	3.76 W (250 K)[1]
	35	13.785-14.085 µm	3.11 W (240 K)[1]
	36	14.085-14.385 µm	2.08 W (220 K)[1]

3. THE MODIS GEOLOCATION PRODUCT (MOD03)

Geolocation for the MOD14 files is available in the corresponding MOD03 product (Figure 2), available from NASA. For every five minute MODIS granule there is a MOD03 product with two grids. One grid reports the latitude for the center of each MODIS pixel and the other reports the longitude.

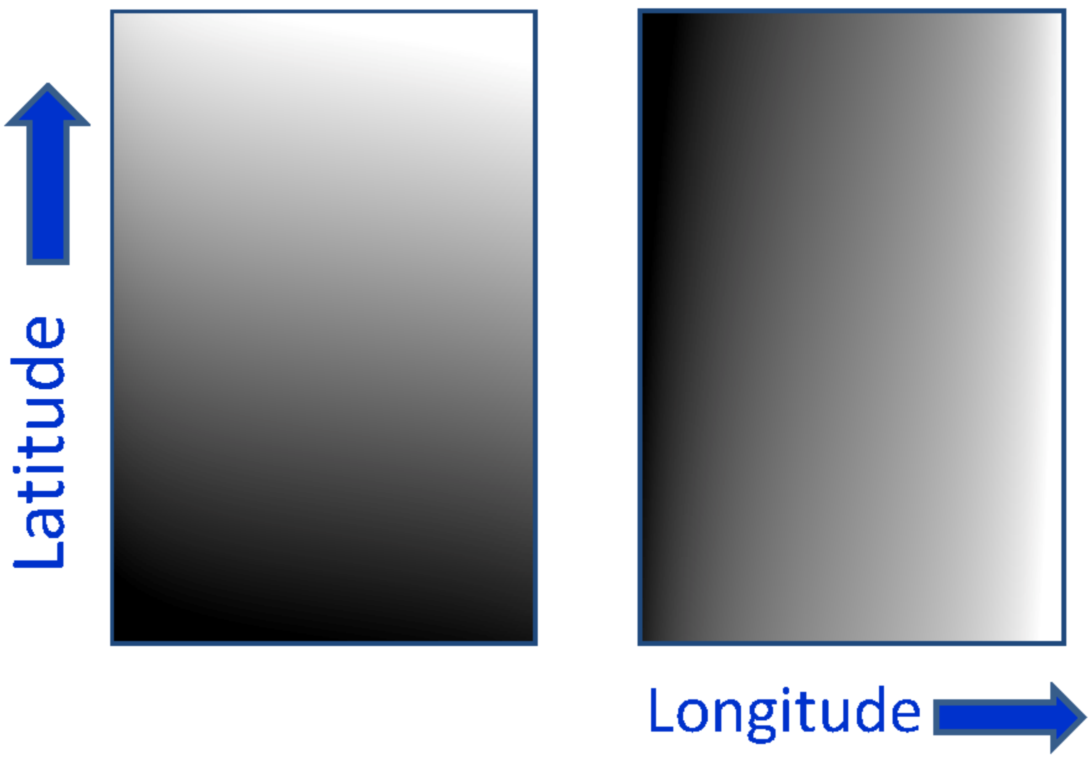

Figure 2. For each five minute MODIS granule there is a MOD03 product, which contains a grid of latitudes (on left) and longitudes (on right).

4. PREVIOUS MODIS GAS FLARING STUDIES

Several years ago NASA funded Dr. Sonia Gallegos of the Naval Research Laboratory to study the detection of gas flares in the U.S. Gulf of Mexico. The objective was to estimate gas flaring volumes. The investigator worked with radiance calibrated MODIS image data (not the MODIS fire products). The study found that MODIS was capable of frequently detecting the larger gas flares operating in the Gulf of Mexico. The investigator attempted to correlate the reported gas flaring volumes on individual dates with MODIS thermal anomaly detections. The investigator found that the test sites with known gas flaring volumes were in some cases not detectable with the MODIS data. She concluded that MODIS data would only be marginally useful for the daily estimation of gas flaring volumes. The investigators did not process enough MODIS image data to test the systems capability for annual estimation of gas flaring volumes.

5. PROJECT OBJECTIVES

The current contract had the following objectives:

1) To investigate the potential for using the operational MODIS fire product (MOD14) to detect and estimate gas flaring volumes.

2) To compare the MOD14 results with DMSP to see if it possible to confirm the trends found with DMSP.

3) To evaluate the potential for detecting offshore flares with MODIS. If this capability could be confirmed it would add weight to the call for expanding the operational fire product processing for MODIS and VIIRS to offshore areas having flares.

6. METHODS AND RESULTS

6.1 Investigation with the MOD14 Products

Download of MODIS Data: The analysis area for the MODIS study was defined to cover the onshore flares that had been identified with DMSP. NGDC used existing NASA spatial / temporal query tools to search the MODIS archive, generating annual lists of file names organized by satellite (Terra and Aqua). These lists were used to download specific granules via ftp. The MOD14 products were downloaded from the USGS EROS Data Center. The MOD03 products were downloaded from the NASA Goddard Space Flight Center. The names of the downloaded files were cross checked against the compiled list to ensure that all the overpasses were obtained. Files were downloaded for collection were from the TERRA satellite for years 2000 – 2009 (2000 partial year) and the AQUA satellite for 2002 – 2009 (2002 partial year). For year 2009 processing was expanded to all the granules for both satellites (not just those containing flares). Table 2 summarizes number of files and data volume downloaded.

TABLE 2
MODIS MOD03 and MOD14 Data Download Summary

PRODUCT	SOURCE	Granule Size	Annual Volume	Files per day	Project number of files	Project Volume
Geolocation MOD03	NASA Goddard Maryland	30 MB	1 TB	100	660,000	18 TB
Fire MOD14	USGS Land Processes DAAC, South Dakota	0.3 MB	10 GB	100	660,000	180 GB

Geolocation. Each of the MOD14 products was geolocated using the latitudes and longitudes provided in the corresponding MOD03 product. For this task, we used the MODIS Reprojection Tool - Swath package (MRTSwath), available from the USGS Land Processes DAAC. MRTSwath has the advantage of having freely available source and executables, highly configurable and scriptable – able to run large batches of granules on our processing cluster, directly ingests the MOD03 geolocation files. As we began testing of MRTSwath we discovered three obstacles:

1. The MRTSwath implementation of the nearest neighbor resampling method returns an average when more than one input pixel falls in an output grid cell. This happens at the edge of every scan, i.e. the "bowtie effect". It is incorrect to average the MOD14 firemask data as the values correspond to a class (i.e. water, fire). To resolve this problem modifications were made to the MRTSwath source files to add a new resampling method, nearest neighbor – first in (NNF).

2. The MOD14 FRP data is a list of floating-point data. MRTSwath handles only image input of type byte or 16-bit integer. To resolve this problem we created two dimensional integer arrays containing line and sample positions. Process these arrays using MRTSwath, creating 30 arc-second "lines" and "samples" grids

which can be used as a lookup table from the 1-D FRP data into output space. This solution was chosen in lieu of making a 2-D integerized representation of the FRP data for 2 reasons: Producing lines and samples grids allows the MOD14 to be processed independent of the MOD03 files. Having reprojected samples grids enable the composites to be constrained based on scan angle without reprocessing the granules.

3. MRTSwath crashes when it encounters longitude discontinuities (e.g. at -180/180 boundaries) causes MRTSwath. Such discontinuities are more common at high latitudes. Our approach was to first reduce the number of discontinuities by restricting processing to latitudes between +/-75 degrees. Then, each file was screened prior to processing to identify those with longitude discontinuities. In these cases a temporary MOD03 file was created by shifting longitude range from [-180,180] to [0,360]. Then it was possible to geolocate the MOD14 product, and afterwards shift the longitude range back to [-180,180].

The modified MRTSwath was used to generate 30 arc second grids for each of the MOD03 products (Figure 3).

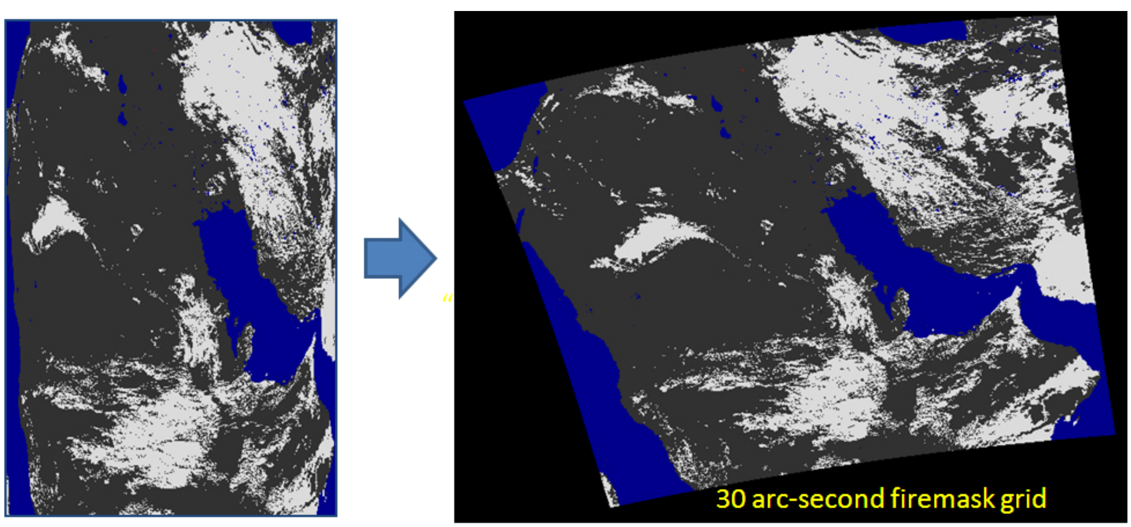

Figure 3. The MOD14 are bitmaps that directly overlay the MODIS granules with no geolocation. Using a modified version of MRTSwath and the MOD03 products, we geolocated each of the MOD14 products to 30 arc second grids, matching the reference grid used in the DMSP analyses of gas flaring.

Construction of Annual Cloud-Free Composites: The 30-arc second firemasks and FRP grids were composited, creating a suite of files including the total number of coverages, cloud-free coverages, average FRP per square kilometer band and percent frequency of fire detections (Figure 4). The average FRP and percent frequency of fire detection were then multiplied by each other to form the FRP_x_PCT which is then used in the gas flaring analyses (Figure 4). The full list of products is listed in Table 3. In reviewing the products we found that gas flares are point-sources of persistent fire activity. They occur with higher percent frequency, and lower average frp/km^2 values than other fire types. An examination of the average FRP and PCT data reveals that it is easy to distinguish gas flares from biomass burning (Figure 5) based on the spatial persistence of the gas flares. Biomass burning is highly variable in average FRP, but has very low persistence (PCT). In contrast, flares are relatively low in average FRP, but higher PCT values.

Development of a BCM Calibration: The same vector polygons used for the DMSP calibration were used for the MODIS analysis. Only onshore reference flares and countries with reported BCM and no offshore flaring were used in the calibration. Figure 6 shows the integrated sum of FRP_x_PCT within the polygons containing the flares versus reported BCM.

Estimation of BCM Detection Limits: By examining the BCM values for flares that were not detected in the MOD14 composites it is possible to estimate the BCM detection limits for the MOD14 product. This can be considered as the detection limits of the MODIS sensor, combined with the detection limits of imposed by the MOD14 fire detection algorithm and the settings used to define an active thermal anomaly. Figure 7 shows that it is rare for the MOD14 product to detect flares with less than 0.2 BCM of gas flared per year. Out of 108 reference points with reported BCM, only seven were detected in MOD14 composites (a 6.5% success rate). In contrast all 25 reference points with reported BCM over 0.2 were detected. Based on this we place the MOD14 BCM detection limit at 0.2. Another aspect of the detection limit issue is the relatively low frequency of detection found for major flares in the MOD14 product. As an example, consider the matched pair of Band 22 versus MOD14 for the Southern Iraq / Northern Persian region (Figure 8).

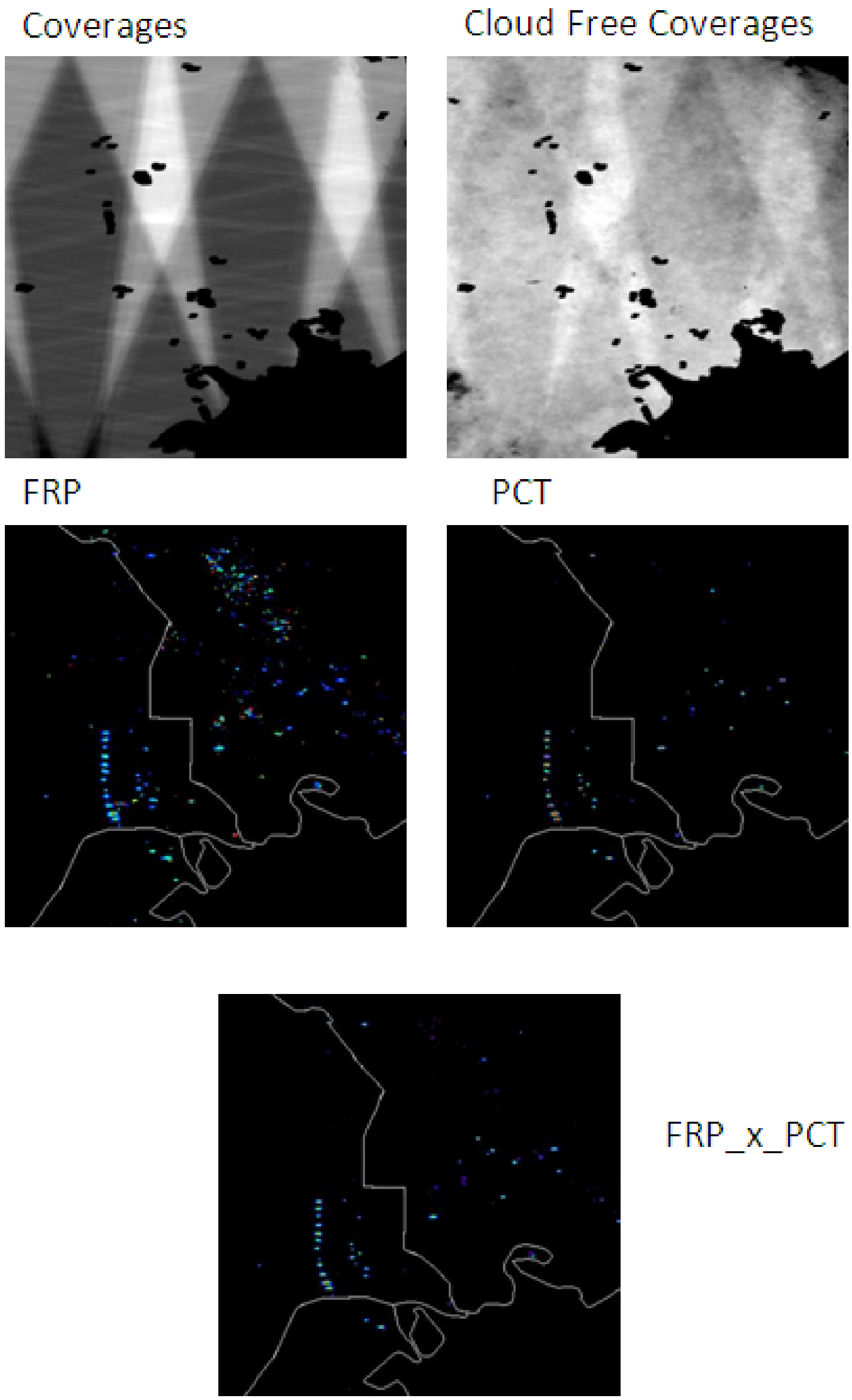

Figure 4. Samples from the MOD14 global composite from the Terra satellite in year 2004 covering the northern end of the Persian Gulf and the string of flares at Basra, Iraq.

TABLE 3
Product List from the MOD14 Compositing

PRODUCT	WHAT IS IT	FILE SIZE (GB)
avg_frpkm2	The average Fire Radiative Power per km^2	2.8
cvg	Number of coverages	1.4
cf_cvg	Number of Cloud-free coverages	1.4
max_frpkm2	Maximum FRP per km^2 contribution to the average	2.8
min_frpkm2	Minimum FRP per km^2 contribution to the average	2.8
n_frp	The number of fire detections at each pixel	1.4
std_frpkm2	The standard deviation of the FRP at each pixel	2.8
sum_frpkm2	The sum of the FRP at each pixel	5.5
sum_sq_frpkm2	The sum of the squares of the FRP at each pixel	5.5
pct_frp	The percentage of fire detections relative to cloud free observations (i.e. How frequently was a fire detected?)	2.8
avg_frp	The avg_frpkm2 x area = total FRP per pixel	2.8
avg_frp_x_pct	FRP multiplied by percent detection	2.8
Total per satellite year		**34.8**
Total		**626.4 GB**

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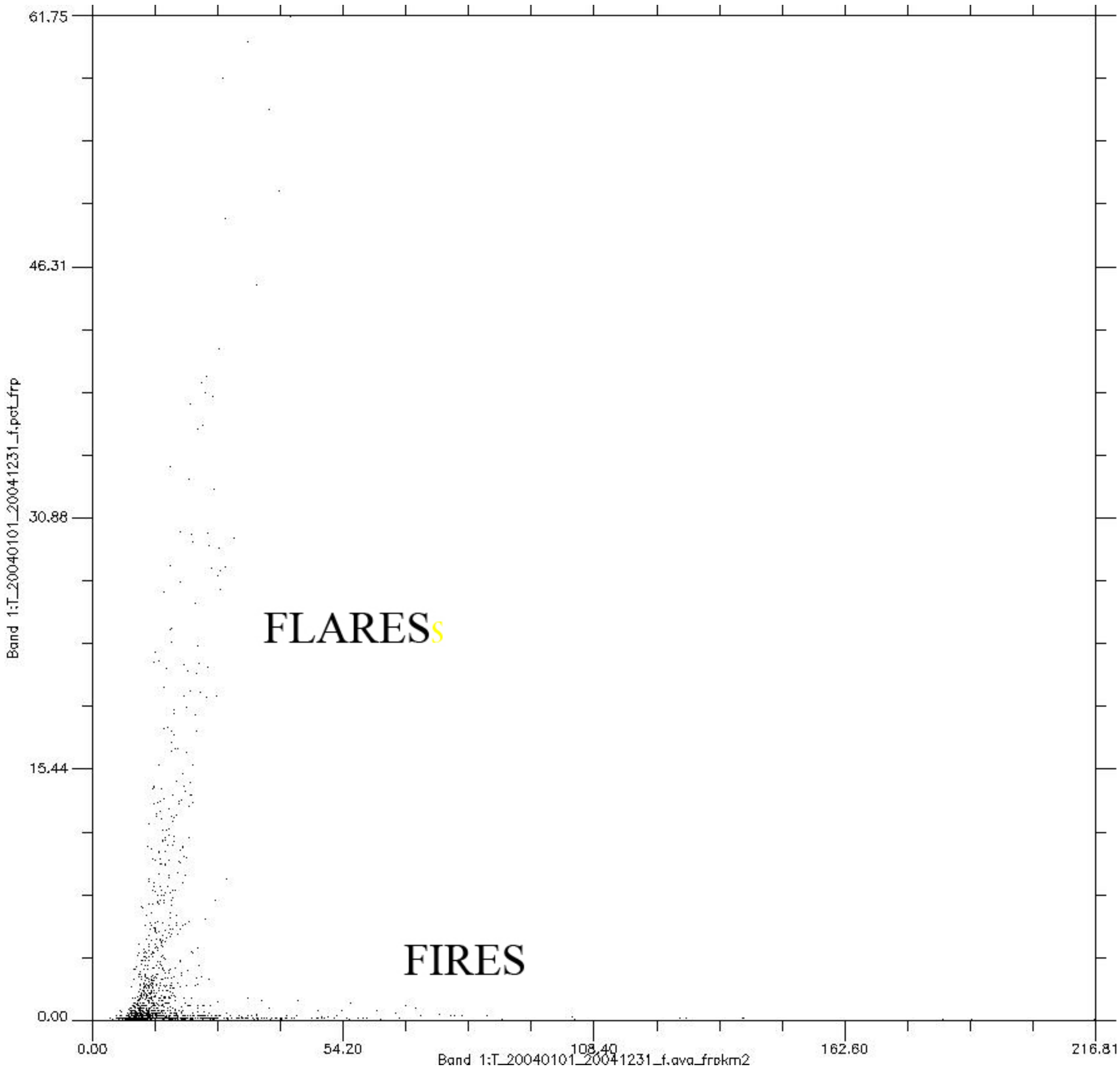

Figure 5. Scattergram of FRP (x axis) versus PCT for gas flares and fires.

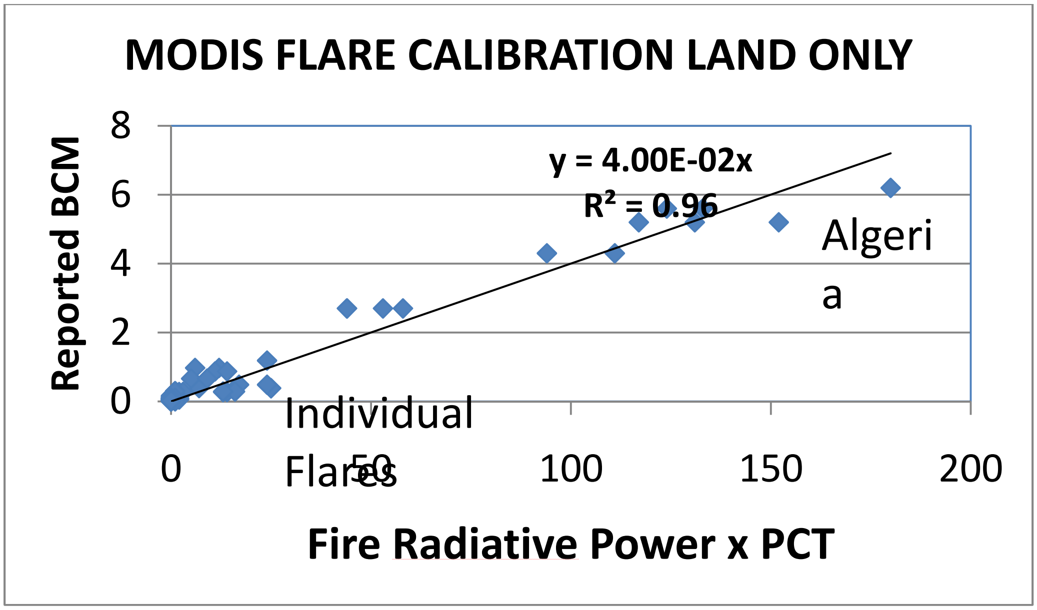

Figure 6. Calibration developed for estimating gas flaring volume (BCM) from the MOD14 composites.

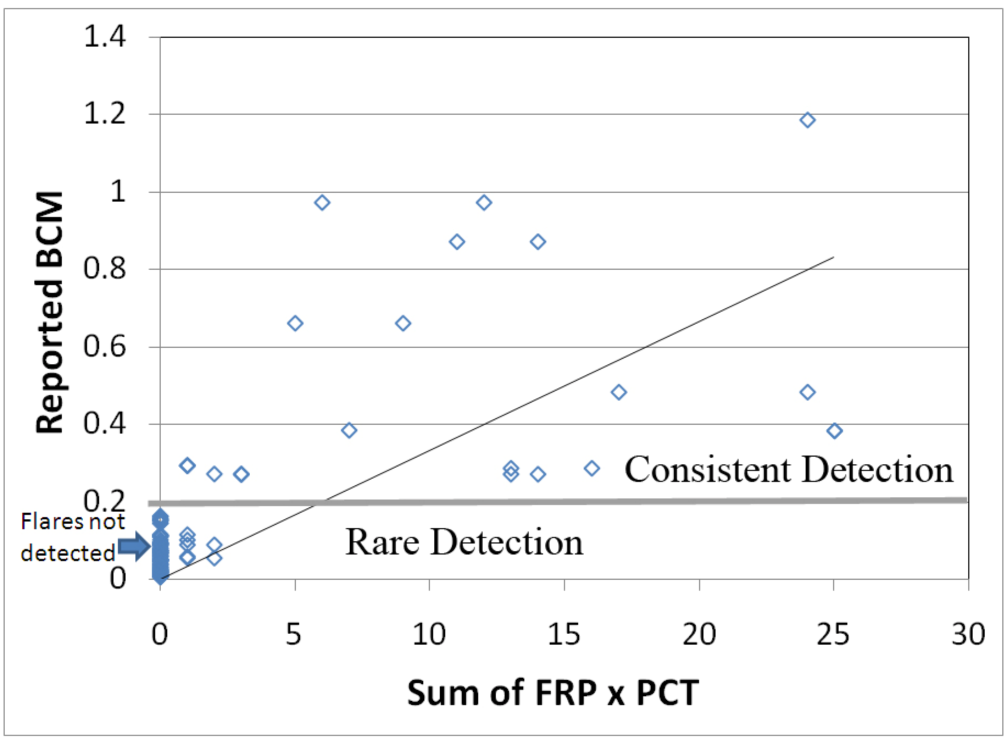

Figure 7. The MOD14 composite detection limit is placed at 0.2 BCM. Flares below 0.2 BCM were rarely detected (seven out 108 cases). In contrast, flares with reported BCM over 0.2 were consistently detected.

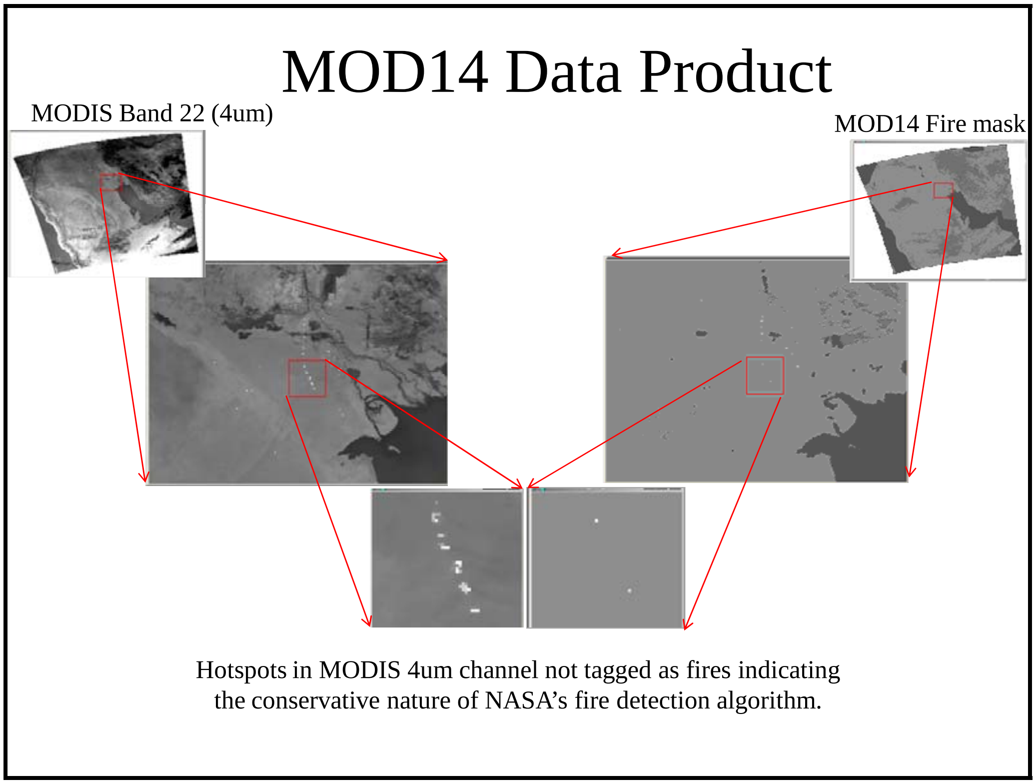

Figure 8. It was noted that the MOD14 fire detection often missed flares that could be visually detected in the in the MODIS 4 um thermal band.

MOD14 Estimation of Gas Flaring Volumes: Based on the calibration developed in Figure 6 we estimated gas flaring volumes for sixty countries from 2000 to 2009 and compared these results to land only flaring from DMSP. For a number of countries, like Nigeria and Algeria, the MOD14 BCM estimates track the DMSP estimates, but are slightly lower (Figure 9). This is consistent with the finding that the MOD14 composites rarely detect flares under 0.2 BCM. However, in other cases, such as Bolivia (Figure 9), the MOD14 BCM estimates vastly exceed the estimates from DMSP. In comparing the global land-only BCM estimates, the MOD14 results follow the trends found with DMSP, but are on average 25% lower (Figure 10).

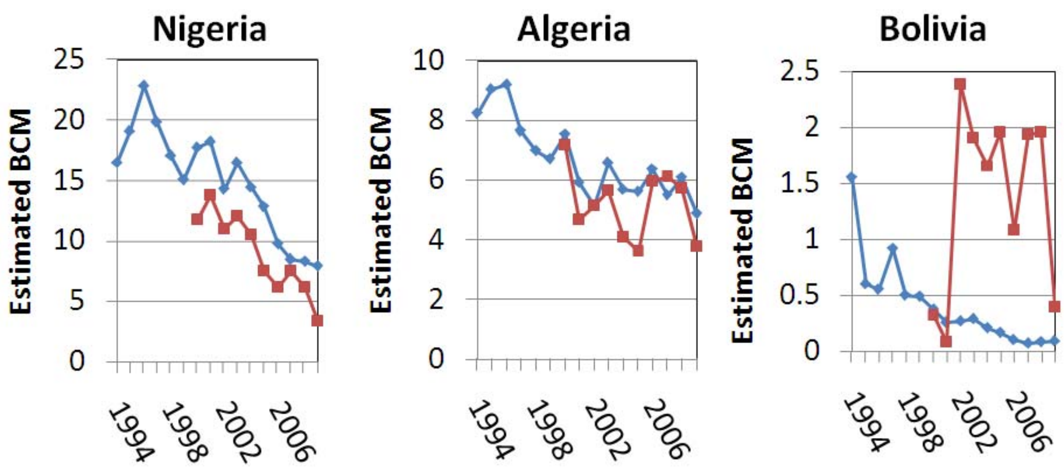

Figure 9. Comparison of DMSP and MOD14 BCM estimates for land-based flaring from Nigeria, Algeria and Bolivia.

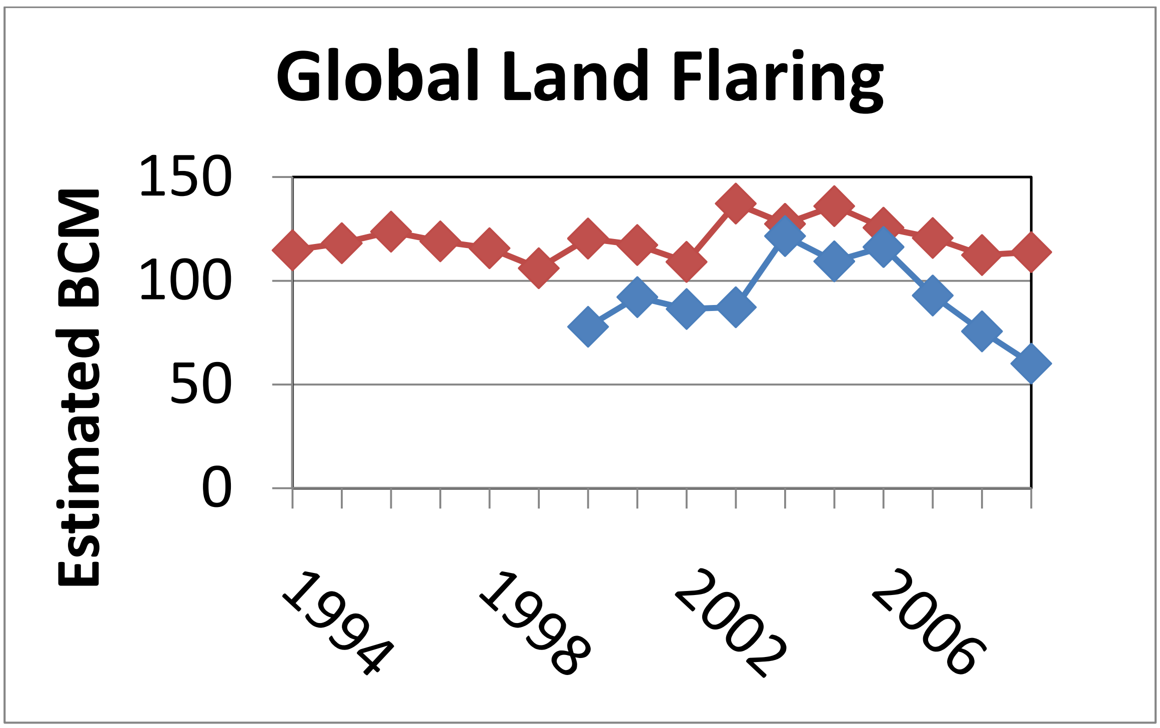

Figure 10. MOD14 versus DMSP global estimates of land-based flared gas volumes.

Examination of MOD14 BCM Estimate Anomalies: In reviewing the MOD14 versus DMSP BCM estimates for individual flares we found smaller flares where the MOD14 yielded low or zero BCM (Figure 11). This can be attributed to the poor ability of the MOD14 composite in the detection of flares with less than 0.2 BCM of flared gas per year. Another observed phenomena in the MOD14 derived BCM estimates of individual flares is the “monster flare”. These are flares with MOD14 BCM estimates in excess of 3 BCM. Often the MOD14 estimates for the monster flares are far in excess of the DMSP estimates and appear to be unrealistically high. This is shown for a large gas flare in Kazakhstan in Figure 11.

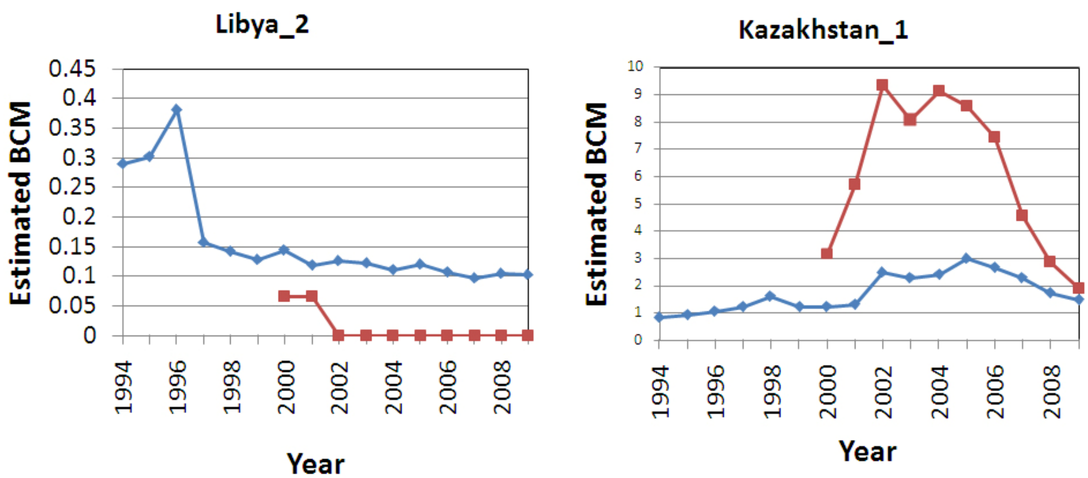

Figure 11. Examples of anomalies found in the BCM estimates from individual flares sites with the MOD14 composites. Small flares, with less than 0.2 BCM estimated from DMSP, are frequently not detected in the MOD14 composite. In contrast, the MOD14 BCM estimates become unrealistically high for flares with over 2 BCM estimated from DMSP.

What is the cause for the “monster flares”? We reviewed the image data and noticed that the “monster flares” have unusually high PCT values, beyond the levels found in the calibration flare sets. This is shown in Figure 12. While this appears to be the cause, we do not yet understand why these flares are detected with much higher frequency. A companion question is “why are the calibration set flares detected so infrequently?”

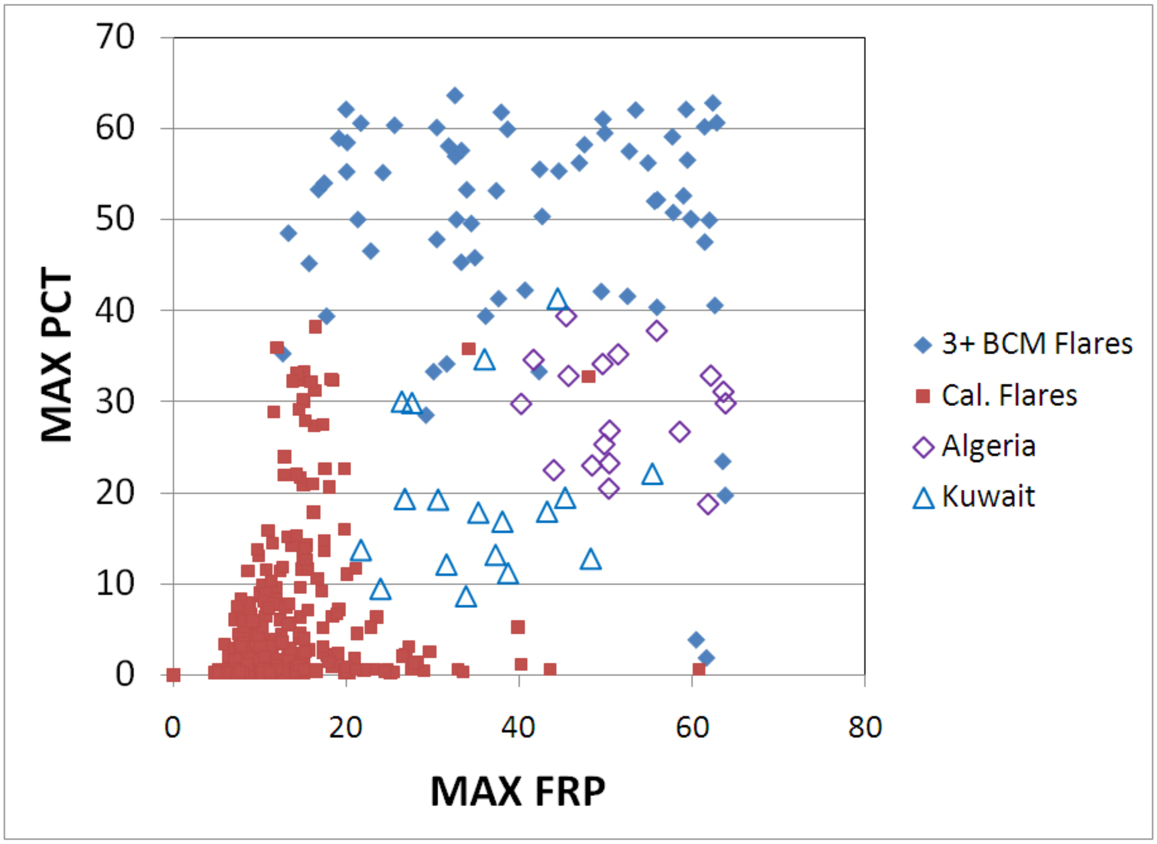

Figure 12. Max FRP versus Max PCT for the calibration flare sets (individual flares, Kuwait, and Algeria), plus the "monster flares" with MODS14 BCM estimates over 3 BCM. Note that the monster flares generally have higher PCT values than the calibration flare sets.

6.2 Offshore Detection of Gas Flares in MODIS Data

We conducted a visual survey of MODIS Band 22 (4-5 um) images in offshore gas flaring regions and confirmed that offshore gas flares are readily visible. Band 22 is the so-called "fire" band, used in the MODIS operational fire detection product (MOD14). Offshore flaring was found in Brazil (Figure 13), India (Figure 14), Nigeria (Figure 15), North Sea (Figure 16), and Persian Gulf (Figure 17).

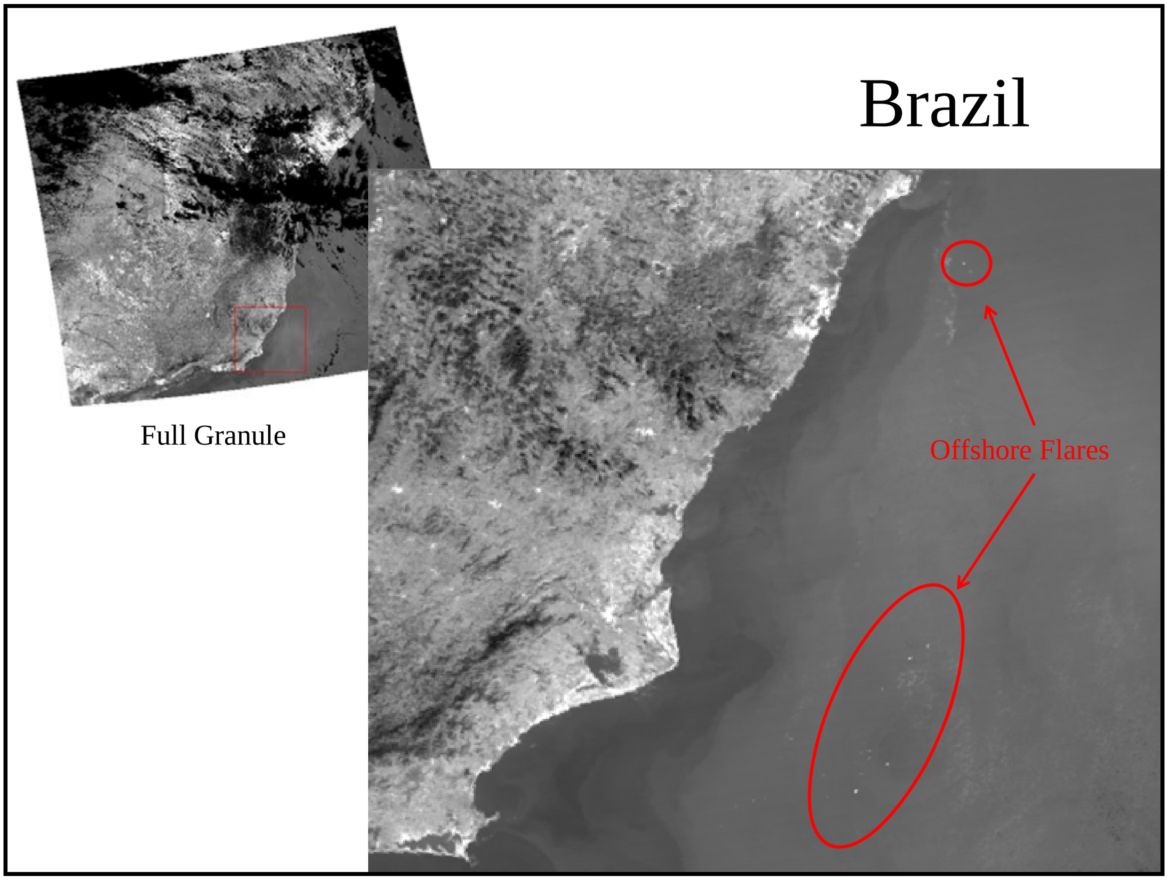

Figure 13. Visual identification of flares offshore from Brazil in MODIS band 22 (4-5 um) image data.

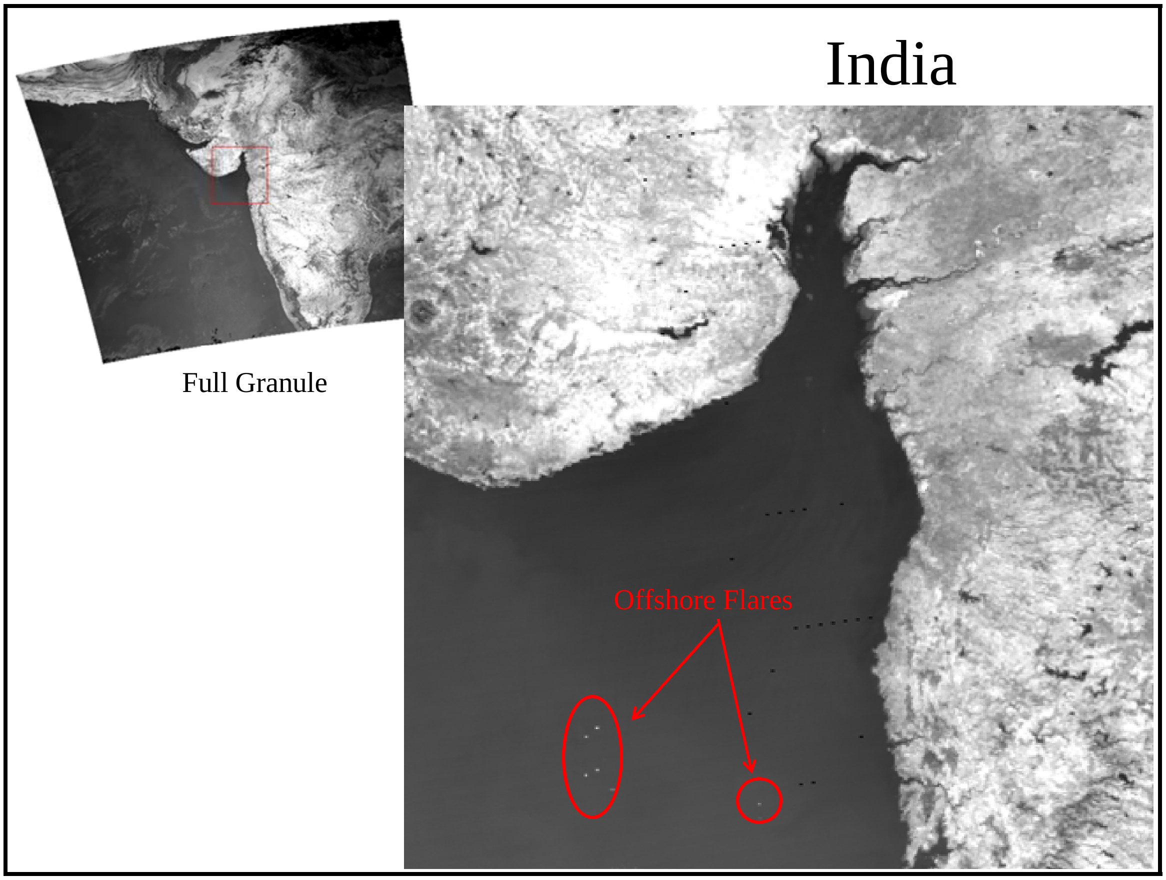

Figure 14. Visual identification of flares offshore from Mumbai, India in MODIS band 22 (4-5 um) image data.

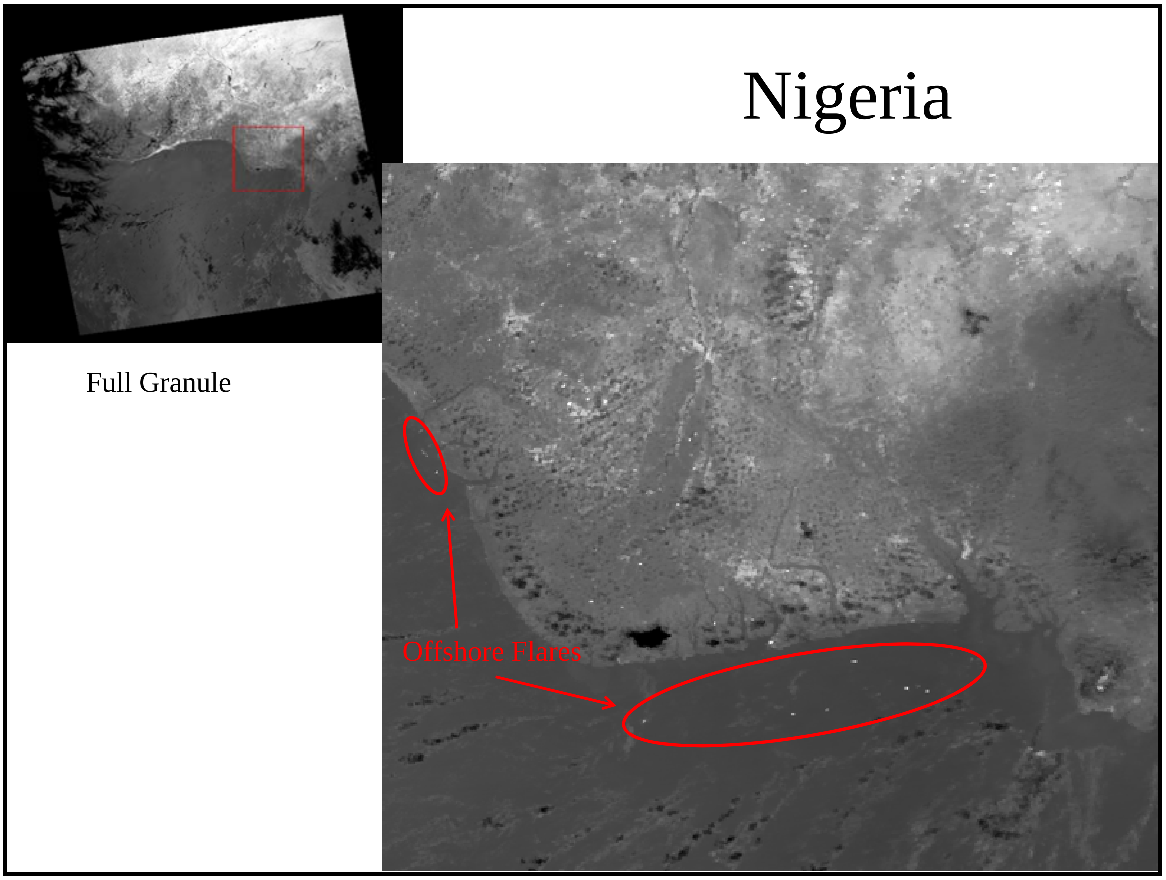

Figure 15. Visual identification of flares offshore from Nigeria in MODIS band 22 (4-5 um) image data.

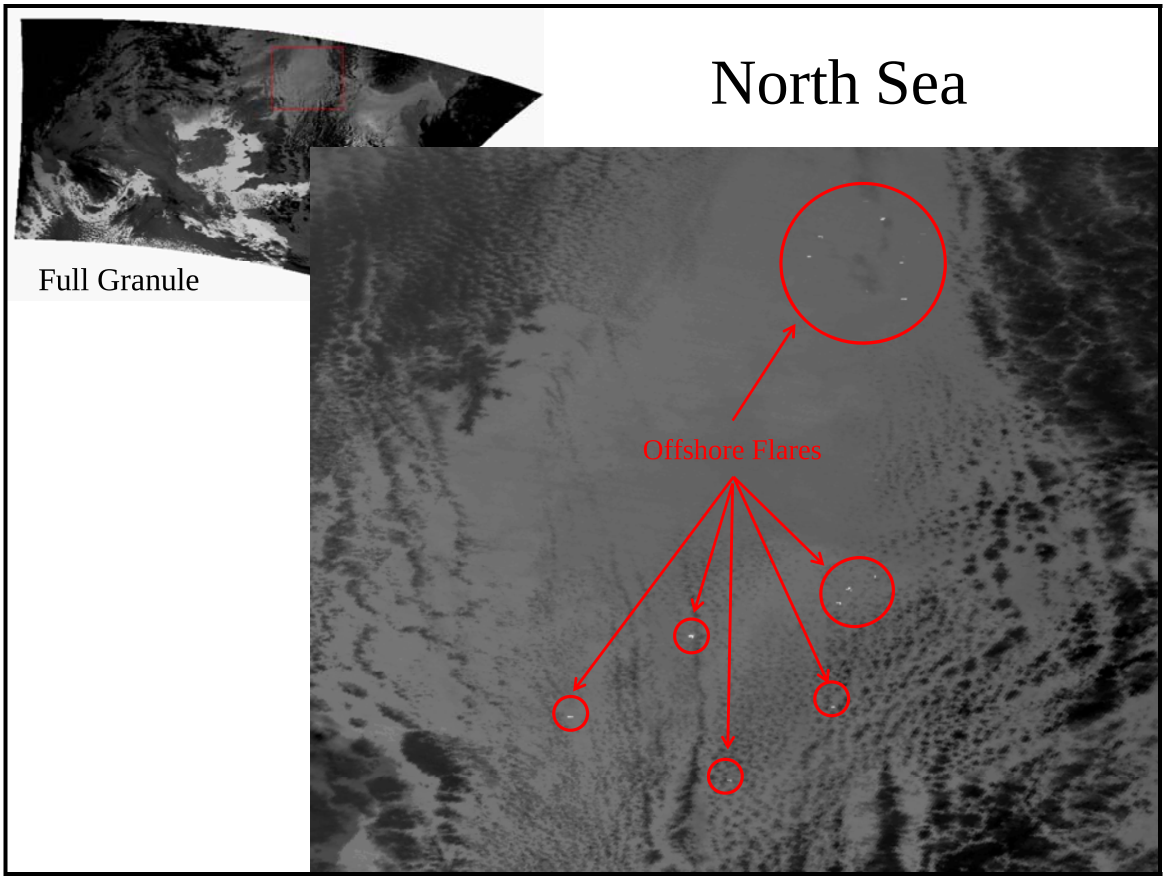

Figure 16. Visual identification of flares in the North Sea in MODIS band 22 (4-5 um) image data.

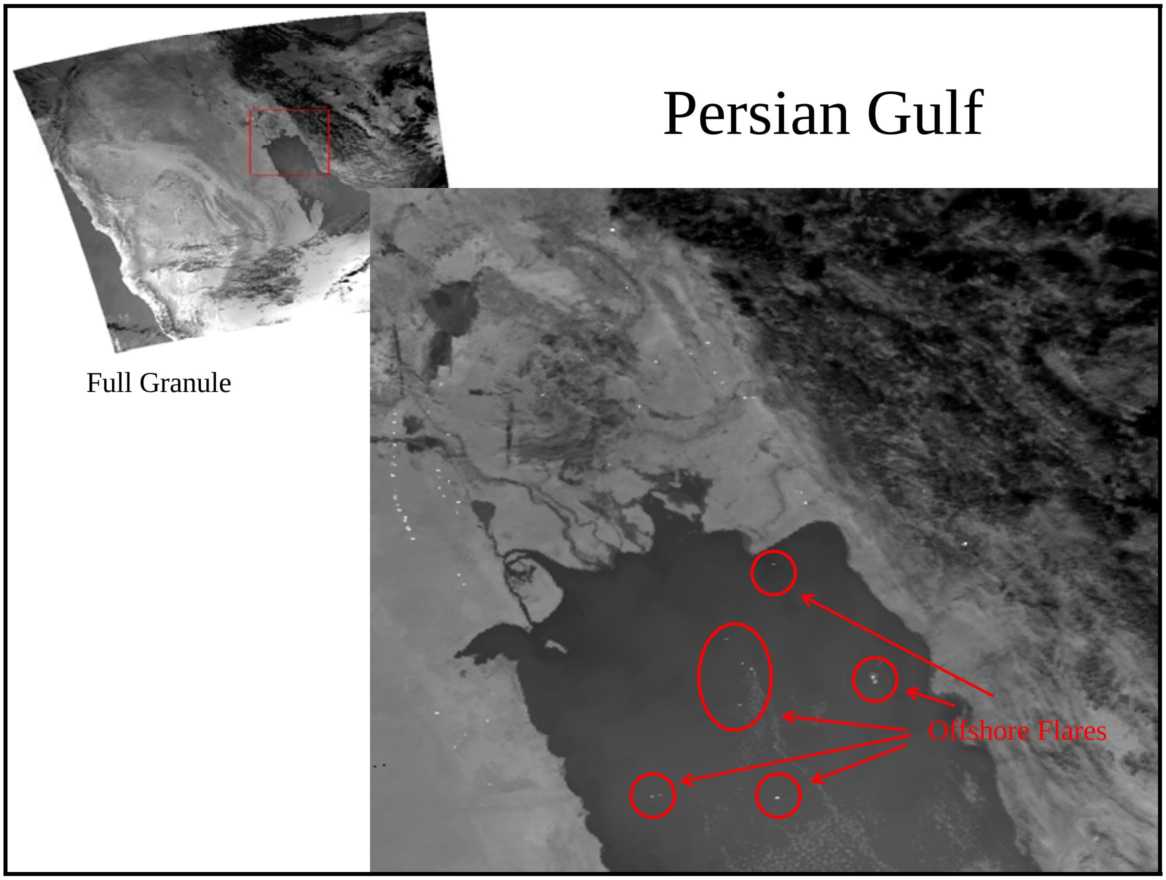

Figure 17. Visual identification of flares in the northern Persian Gulf in MODIS band 22 (4-5 um) image data.

6.3 Compositing the MODIS Fire Detection Bands

The results with the MOD14 composites suggest that it may be possible to derive better detection and better estimation of gas flaring volumes by processing the original MODIS granules. We made two styles of annual cloud-free composites for a test area – Nigeria – for year 2004 using data collected by the MODIS instrument flown on the Terra satellite. The first is simply a cloud-free composite of the brightness temperatures observed in the two spectral bands used in the MODIS fire detection algorithm – band 22 (T4 and 4 um) and band 30 (T11 at 11 um). In the MODIS fire detection algorithm active fires are detected based on their anomalously high temperatures in T4 relative to T11. However, only a few flares could be seen in the T4 annual composite (Figure 18). Finding this, we then made a cloud-free annual composite of the temperature differences between T4 and T11. The initial product looked similar to the T4 composite (Figure 18) due to the inclusion of negative values where T11 exceeded T4. By only compositing data where T4 exceeded T11 an image (T4mT11) was generated with clear indications of gas flares

(Figure 19). However, there is overlap in the range of data values for gas flares and background. To isolate the locations of the flares a high pass filter was applied (Figure 20). A threshold of five was applied to the high pass filtered image (Figure 21), which eliminated the background, preserving the centers of the detected flare locations. A dilation was applied to generate a mask which was used to extract theT4mT11 image values from the original T4mT11 image (Figure 22). We then compared the sum of T4mT11 with the reported BCM for year 2004 reference flares in the Nigeria region (Figure 23). In reviewing the reported BCM for reference flares not detected with the T4mT11 product we found that detections were rare for flares with less than 0.05 BCM per year and that flares with over 0.05 BCM were consistently detected. Based on this we place the BCM detection limit for the T4mT11 product at 0.05 BCM. A comparison of the sum of T4mT11 values versus DMSP satellite F15 sum of lights values for reference flares in the Nigeria region (Figure 24) indicates that outside of the lack of detection found for MODIS in gas flares under 0.05 BCM, the two sensors yield comparable values.

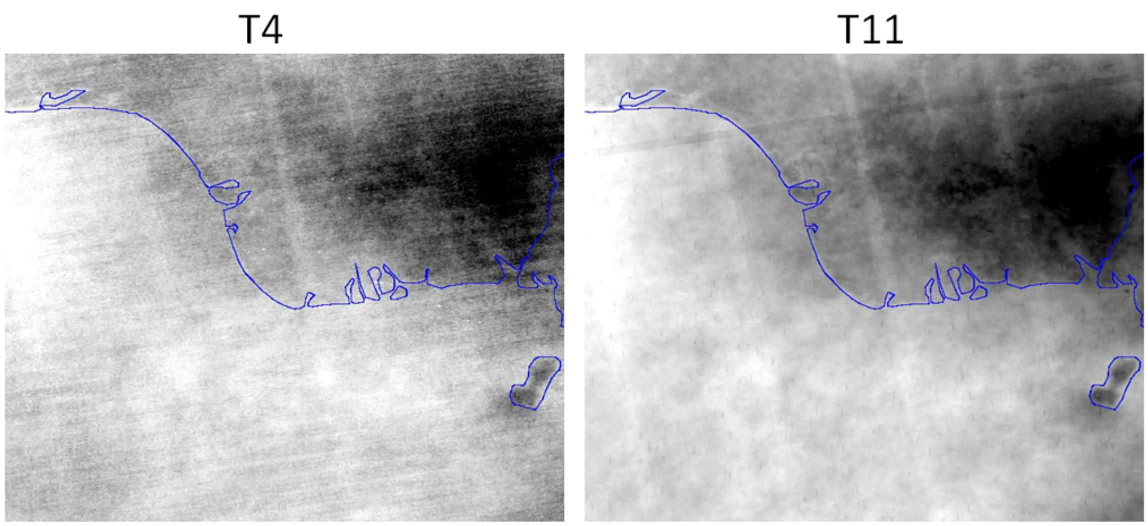

Figure 18. Year 2004 annual cloud-free composites of brightness temperatures for the Nigeria region derived from the Terra MODIS band 22 (T4 at 4 um) and band 30 (T11 at 11 um). Note that there are faint indications of several gas flares (barely visible) in the T4 composite.

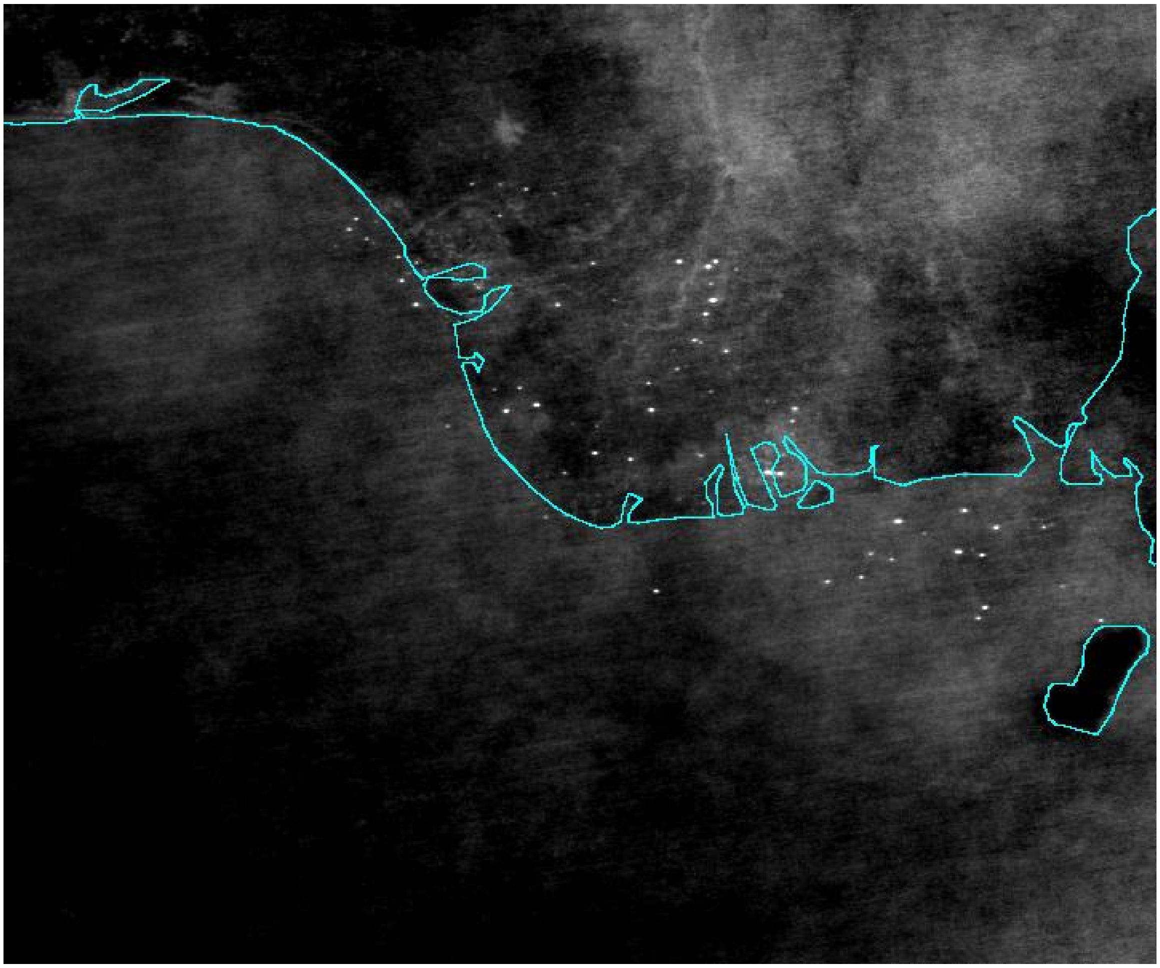

Figure 19. The T4 minus T11 composite (T4mT11). Only data where the T4 temperature exceeded T11 were composited. Note the clear detection of numerous gas flares.

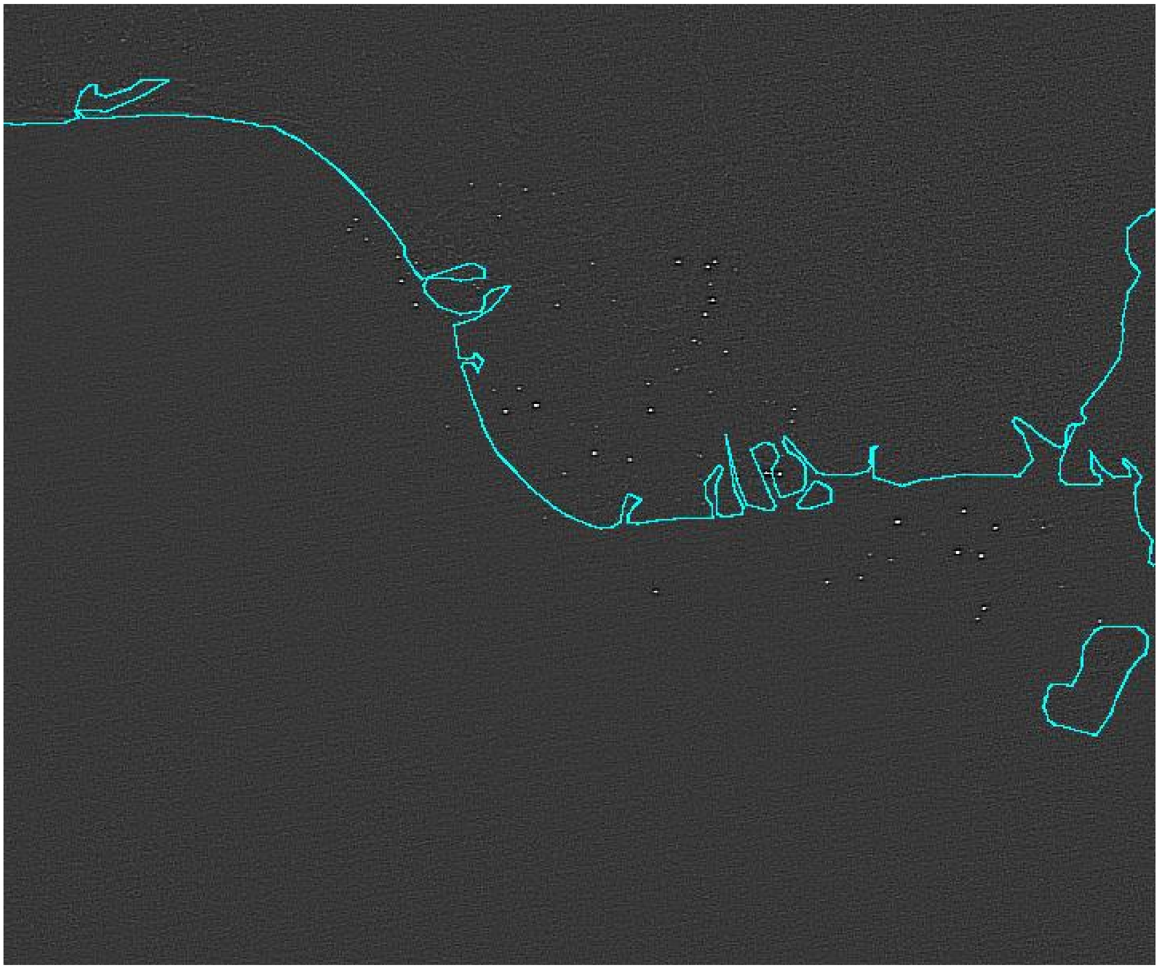

Figure 20. A high pass filter was applied to the T4mT11 image to push down the background.

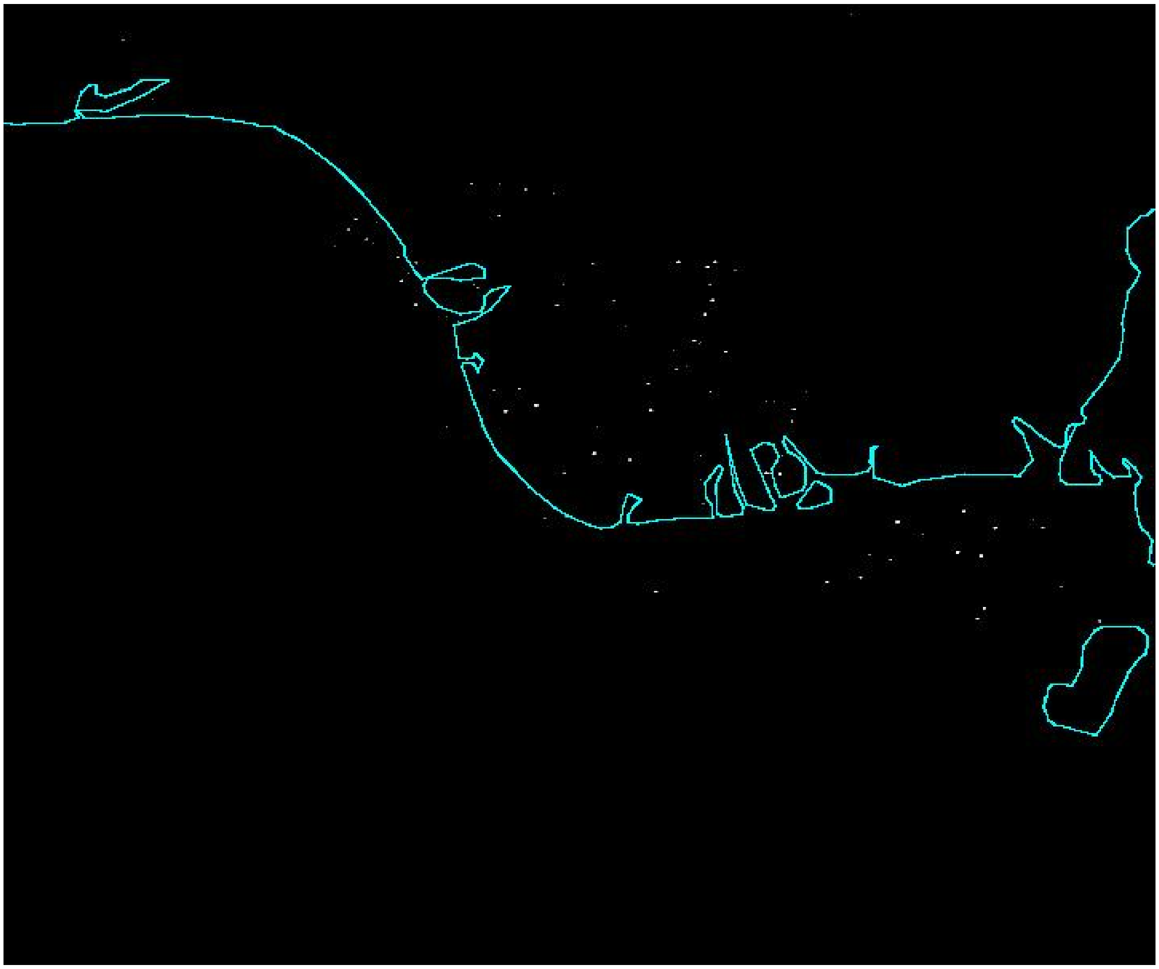

Figure 21. A threshold of five was applied to the high pass filter image to isolate the centers of the gas flares detected in the T4mT11 composite.

Figure 22. A dilation was applied to the Figure 21 image to generate this mask, which was used to extract the T4mT11 image data of gas flares.

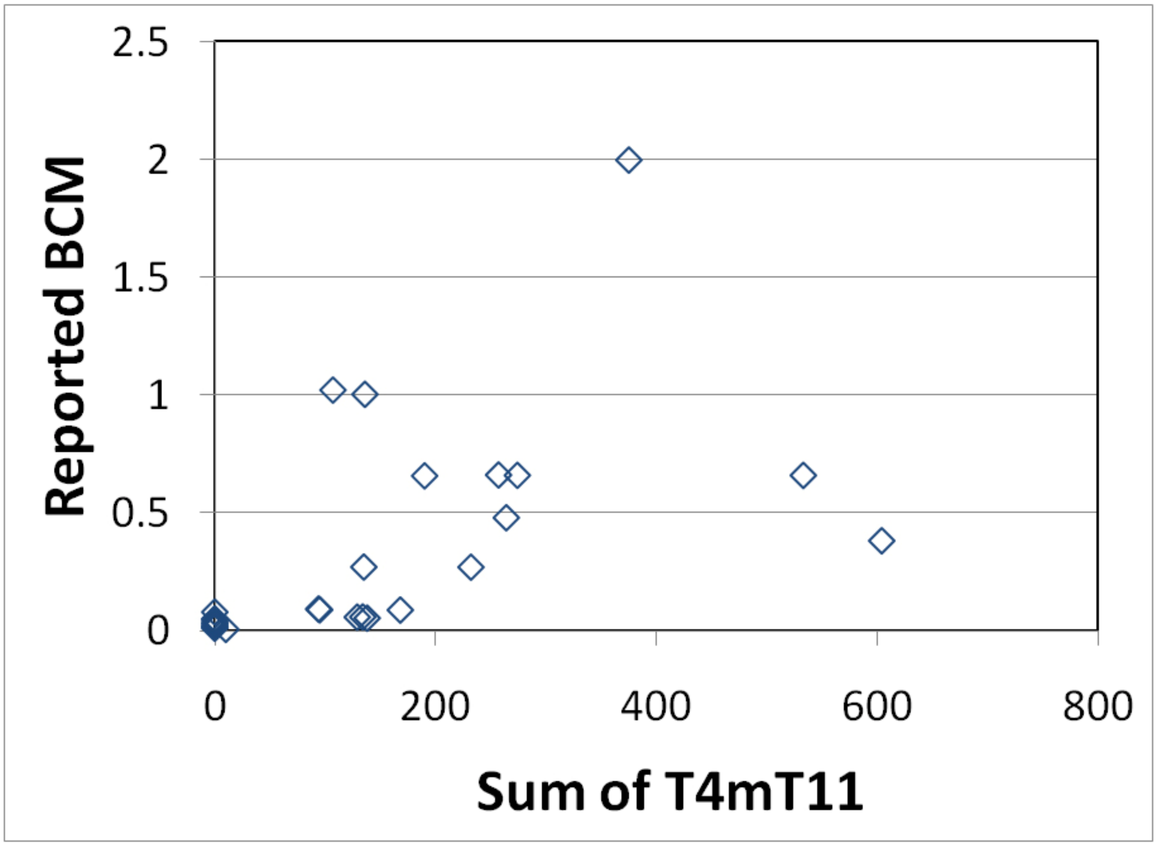

Figure 23. Comparison of the sum of T4mT11 values versus reported BCM for the reference gas flares in the Nigeria region for year 2004.

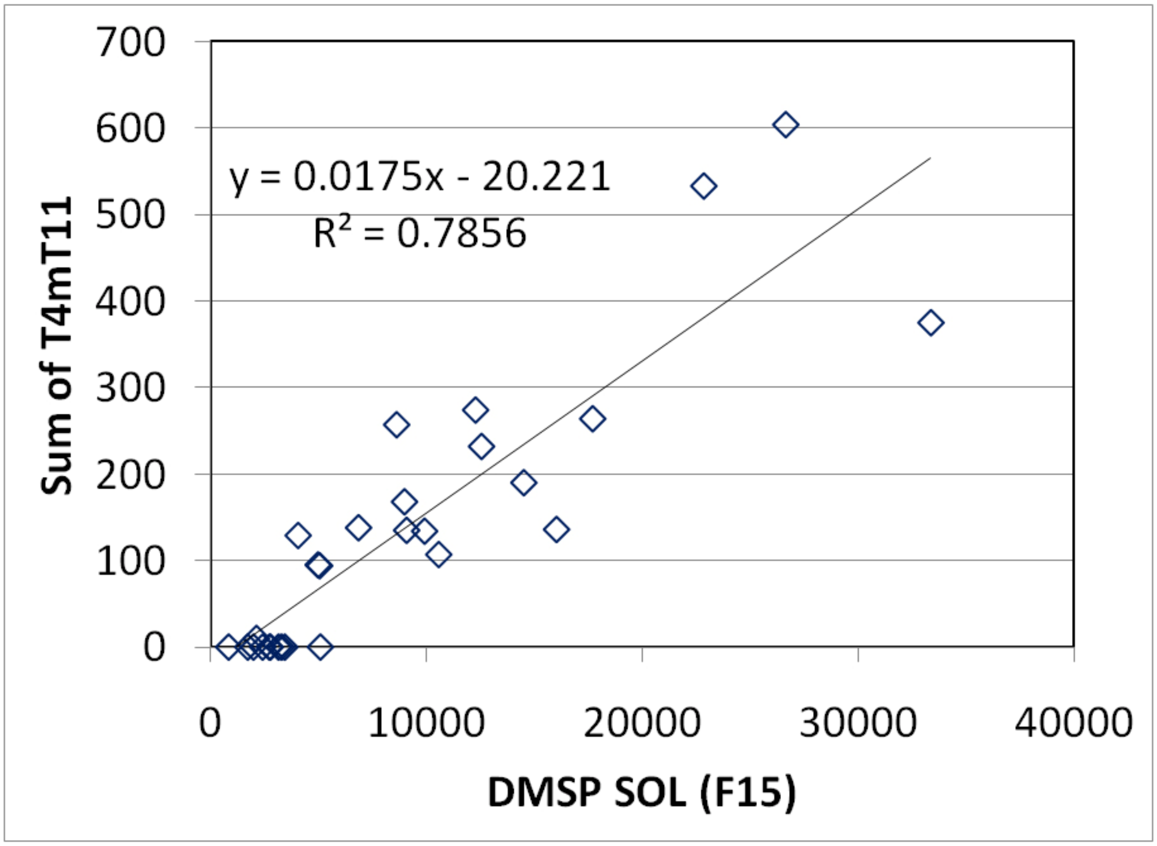

Figure 24. Comparison of DMSP satellite F15 sum of lights (SOL) versus MODIS sum of T4mT11 values for reference flares in the Nigeria region in year 2004. The cluster of MODIS detections near zero is an indication that DMSP has lower detection limits for gas flares than MODIS. The general agreement between the two systems for the other flares can be attributed to the fact that both sensors are detecting radiant emissions from combustion at these sites, albeit at different wavelength regions.

7. CONCLUSIONS

Our conclusion is that the NASA's operational fire product from the MODIS sensor data (MOD14) is fundamentally flawed for the detection and estimation of gas flaring volumes. There are five basic problems with MOD14 for the annual estimation of flared gas volumes:

1) Offshore regions and lakes are not processed – thus there is no detection of offshore flaring or flares present in lakes (e.g. in places like Siberia).

2) The MOD14 skips over many flares that can be seen visually in the thermal band imagery. This results in an under sampling of the available signal coming from gas flares. The MOD14 algorithm was developed for operational

near real time detection of fires, for use by land and forest managers who deal with fires. The settings are intentionally conservative to avoid "false alarms" in the detection of fires. So it is understandable that it does not work well for gas flares.

3) The MOD14 rarely detects flares with annual BCM levels under 0.2 BCM.

4) With the constraint of only using land based reference data (reported BCM) for individual flares and countries leaves the calibration for estimation of gas flaring volumes sparse when compared to DMSP.

5) We found a set of flares yielding unrealistically high BCM estimates (greater than three BCM) using the MOD14 composites. Most of these "monster flares" have unusually high percent frequencies of detection (PCT), which pushes their average fire radiative power times PCT values to unrealistically high levels.

To get around the limitation of the MOD14 product, we developed a capability to make cloud-free composites of the brightness temperatures differences for the two thermal bands used in MODIS fire detection algorithm. The prototyping was done for the Nigeria region for year 2004 using MODIS data acquired from the Terra satellite. The product is referred to as T4mT11 since it is based on the temperature difference in the thermal bands at 4 and 11 um. These are the same spectral bands used for operational fire detection in the MOD14 product. Examination of the T4mT11 results indicates it is possible to achieve a fourfold improvement in the BCM detection limit when compared with the MOD14 composite. We place the T4mT11 detection limit at 0.05 BCM and the MOD14 detection limit at 0.2 BCM. Comparison of the sum of T4mT11 versus the sum of lights from DMSP for year 2004 in the Nigeria region indicates that the two products are yielding comparable results. By including observations of offshore flares and increasing the number of detections in a year over the MOD14 product for onshore flares, it may be possible to develop a BCM calibration for the T4mT11 product that would resolve the "monster" flare situation encountered with the MOD14 product.

While the detection limit achieved with MODIS (0.05 BCM) is not as low as DMSP (0.015 BCM), there are compelling reasons to consider the reprocessing of the MODIS archive for gas flares:

A) MODIS is capable of acquiring larger numbers of observations, with a more even distribution through the day and throughout the year. With two MODIS sensors in operation, there are generally viewing opportunities in the morning, afternoon, early evening, and after midnight. In contrast DMSP is restricted to early evening observation. The MODIS observations are not seasonally restricted, which is the case for DMSP. At mid-to-high latitudes no useable DMSP observation are acquired during summer months due to solar contamination. The MODIS observations are not restricted by lunar phase. In contrast, the only DMSP data being used are from the dark portions of lunar cycles.As a result, each MODIS is capable of providing eight times as many observations as a single DMSP satellite (Figure 31).

B) The OLS instrument has no on-board calibration and gas flares often saturate in the low light imaging band. In contrast, gas flares rarely saturate in the MODIS thermal bands and the MODIS has on-board calibration.

C) Continuity. While the two MODIS instruments are past their design life, they continue to collect data. The follow on to MODIS and the DMSP OLS sensor is the VIIRS (Visible Infrared Imaging Radiometer Suite). The first VIIRS is slated for launch in 2011. VIIRS will have the MODIS fire detection band, plus a low light imaging band like the OLS. VIIRS instruments are expected to fly in a series for several decades. Thus, by reprocessing the MODIS archive for gas flares it will be possible to build a continuous time series of calibrated gas flaring observations back to year 2000.

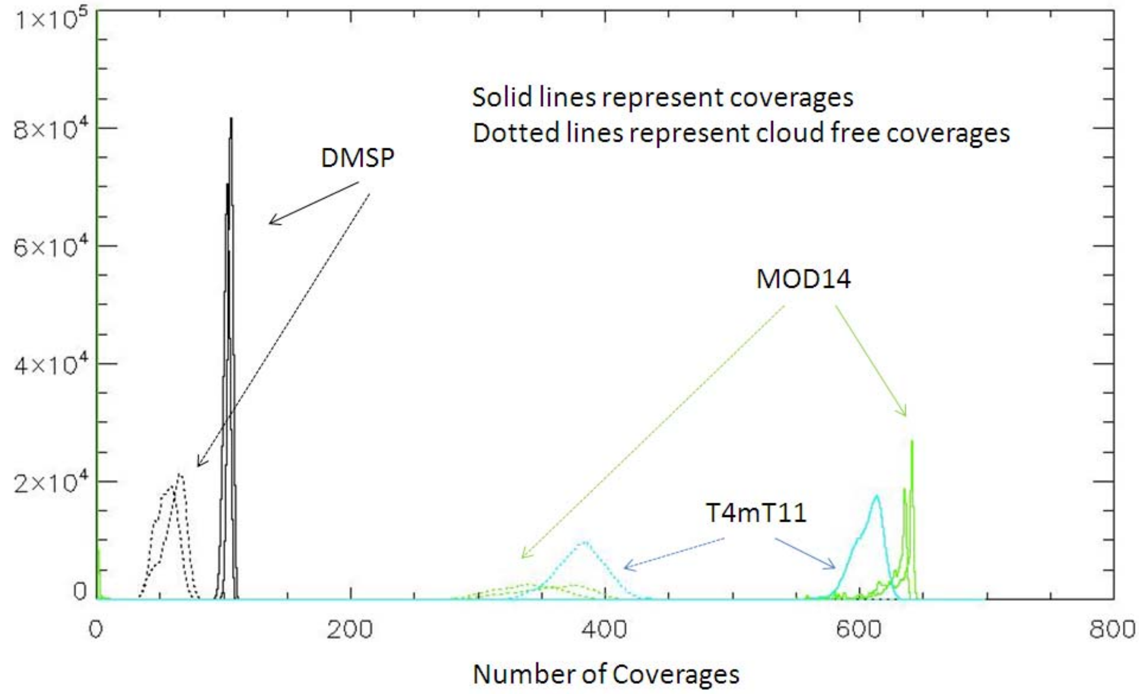

Figure 31. Histograms for coverages and cloud-free coverages for year 2004 in the Nigeria study area from DMSP satellite F14 and F15, the MOD14 composites from Terra and Aqua, and the T4mT11 composite from Terra. Note that each MODIS collects eight times as many observations as a DMSP satellite in a year.

8. RECOMMENDATION

Our recommendation is that the full MODIS archive be processed for gas flares. Prior to doing this, a fine tuning should be done for the T4mT11 product. Our estimate is that this will require the download and processing of twice as much data as the MOD14 study required. This is feasible given the bandwidth and processing facilities available at NGDC.