Remote Sensing of Environment 83 (2002) 244–262

Remote Sensing of Environment

www.elsevier.com/locate/rse

The MODIS fire products

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Received 20 February 2002; received in revised form 17 April 2002; accepted 24 April 2002

Abstract

Fire products are now available from the Moderate Resolution Imaging Spectroradiometer (MODIS) including the only current global daily active fire product. This paper describes the algorithm, the products and the associated validation activities. High-resolution ASTER data, which are acquired simultaneously with MODIS, provide a unique opportunity for MODIS validation. Results are presented from a preliminary active fire validation study in Africa. The prototype MODIS burned area product is described, and an example is given for southern Africa of how this product can be used in modeling pyrogenic emissions. The MODIS Fire Rapid Response System and a web-based mapping system for enhanced distribution are described and the next steps for the MODIS fire products are outlined.

1. Introduction

The Moderate Resolution Imaging Spectroradiometer (MODIS) was launched on the Terra platform in December of 1999, as part of NASA's Earth Observing System (EOS). The MODIS instrument, which began collecting image data in February 2000, is generating a number of land surface products to meet the goals of NASA's Earth Science Enterprise (Justice et al., 1998). The MODIS Fire Products are designed to provide information for both global change science and practical applications (Justice & Korontzi, 2001; Kaufman, Justice et al., 1998; Kaufman, Kleidman, & King, 1998). The MODIS Fire Team is developing and testing two types of fire products: active fire products which give the location of burning fires and a burned area product which gives the extent of burn scars over a specified time period.

Primary emphasis during the first 18 months since launch has been given to generating and refining the MODIS active fire products. This has involved extensive product quality assessment and establishment of product accuracy by validation activities. The active fire algorithm uses multiple channels to detect thermal anomalies on a per-pixel basis, which in addition to fires, includes high-temperature point sources, such as gas flares and power plants. Secondary emphasis has been given to the development and testing of a MODIS burned area algorithm (Roy, Lewis, & Justice, 2002, this issue). A prototype burned area algorithm, which uses a multidate analysis approach, is currently being tested for southern Africa in the context of the international SAFARI 2000 campaign (Swap et al., 1999), in support of fire emissions calculations.

2. Fire detection algorithm

Active fire detection for MODIS is based on heritage algorithms developed for the AVHRR and TRMM VIRS (Giglio, Kendall, & Justice, 1999; Giglio, Kendall, & Mack, submitted for publication; Justice, Kendall, Dowty, & Scholes, 1996; Kaufman et al., 1990). The algorithm uses brightness temperatures derived from the MODIS 4 and 11 μm channels, denoted by T_4 and T_{11}, respectively.

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0034-4257/02/$ - see front matter
PII: S0034-4257(02)00076-7

The MODIS instrument has two 4-μm channels, numbered 21 and 22, both of which are used by the detection algorithm. Channel 21 saturates at nearly 500 K; channel 22 saturates at 331 K. Since the low-saturation channel is less noisy and has a smaller quantization error, T_4 is derived from this channel whenever possible. However, when channel 22 saturates, or has missing data, it is replaced with the high saturation channel to derive T_4. T_{11} is computed from the 11-μm channel (channel 31), which saturates at approximately 400 K. The 250-m near-infrared band (0.86 μm), averaged to 1-km resolution, is also used to identify highly reflective surfaces that are more likely to cause false alarms. This reflectance is denoted by ρ_2.

The fire detection strategy is based on absolute detection of the fire, if the fire is strong enough, and on detection relative to the thermal emission of surrounding pixels to detect weaker fires. This latter test identifies pixels with values elevated above a background thermal emission obtained from the surrounding pixels. This method accounts for variability of the surface temperature and reflection by sunlight. The following are the steps in the algorithm.

To avoid false detection, all pixels for which $T_4 < 315$ K (305 K at night) or $T_4 - T_{11} < 10$ K (3 K at night) or $\rho_2 > 0.3$ (daytime only) are immediately eliminated as possible fires.

For absolute fire detection, the algorithm requires that at least one of two conditions be satisfied. These are:

1) $T_4 > 360$ K (330 K at night)
2) $T_4 > 330$ K (315 K at night) and $T_4 - T_{11} > 25$ K (10 K at night)

If either of these absolute criteria is not met, the algorithm pursues a relative fire detection in which the fire is distinguished from the mean background values by three standard deviations in T_4 and $T_4 - T_{11}$:

$$T_4 > \text{mean}(T_4) + 3\text{stddev}(T_4)$$

and

$$T_4 - T_{11} > \text{median}(T_4 - T_{11}) + 3\text{stddev}(T_4 - T_{11}).$$

The mean, median, and standard deviations (denoted by "mean", "median", and "stddev" above) are computed for pixels within an expanding grid centered on the candidate fire pixel until a sufficient number of cloud-, water-, and fire-free pixels are identified. A "sufficient number" is defined as 25% of all background pixels, with a minimum of six. Water pixels are identified with an external water mask, and cloud pixels are identified with the MODIS cloud mask product (MOD35). Fire-free background pixels are identified as those pixels for which $T_4 < 325$ K (315 K at night) and $T_4 - T_{11} < 20$ K (10 K at night). If either standard deviation is below 2 K, a value of 2 K is used instead.

The background window is allowed to grow up to 21×21 pixels in size. If this limit is reached and the previous criteria regarding the minimum number of valid background pixels are not met, the relative detection tests cannot be used. If the absolute tests do not indicate that an active fire is present in this situation, the algorithm flags the detection result as *unknown*.

Combining all tests into a single expression, a pixel is classified as a fire pixel in daytime if the following conditions are satisfied:

$$\{T_4 > \text{mean}(T_4) + 3\text{stddev}(T_4) \text{ or } T_4 > 330 \text{ K}\}$$

and

$$\{T_4 - T_{11} > \text{median}(T_4 - T_{11}) + 3\text{stddev}(T_4 - T_{11}) \text{ or } T_4 - T_{11} > 25 \text{ K}\}$$

or

$$T_4 > 360 \text{ K}$$

For the nighttime algorithm they become:

$$\{T_4 > \text{mean}(T_4) + 3\text{stddev}(T_4) \text{ or } T_4 > 315 \text{ K}\}$$

and

$$\{T_4 - T_{11} > \text{median}(T_4 - T_{11}) + 3\text{stddev}(T_4 - T_{11}) \text{ or } T_4 - T_{11} > 10 \text{ K}\}$$

or

$$T_4 > 330 \text{ K}$$

Finally, for daytime observations when sunglint may cause false detections, a fire pixel is rejected if the MODIS 250 m red and near-infrared channels have a reflectance above 30% and it lies within 40° of the specular reflection position.

2.1. Fire detection confidence

A detection confidence estimate is provided as part of the fire product to help users gauge the quality of individual fire pixels, similar to the scheme described by Giglio et al. (submitted for publication). This confidence estimate is used to assign one of the three fire classes (low-confidence fire, nominal-confidence fire, or high-confidence fire) to all fire pixels within the fire mask. Currently, while the product is in provisional status, all detected fire pixels are assigned nominal confidence.

2.2. Total emitted power

Total emitted power value is assigned to each fire pixel. The total emitted power was deemed to be a useful quantity in the estimation of fire emissions (Kaufman, Justice et al., 1998). A relationship between the rate of emitted energy, E_f, and the detected temperature difference in the 4-μm channel was approximated by Kaufman, Justice et al. (1998) and Kaufman, Kleidman et al. (1998):

$$E_f = 4.34 \times 10^{-19}[T_4^8 - \text{mean}(T_4)^8]$$

with units of W/m^2, or, equivalently, MW per pixel.

3. Active fire products

The current MODIS fire products and their release dates are listed in Table 1.

The standard MODIS fire products are distributed from the Earth Resources Observation Systems Data Center (EDC) Distributed Active Archive Center (DAAC) and are defined in HDF-EOS format as Level 2, Level 2G, and Level 3. A description of the different MODIS Land product levels is found in Masuoka, Fleig, Wolfe, and Patt (1998). In addition, a global browse product is generated, primarily for quality assessment (QA), and a rapid response fire product for operational near-real time fire data users.

The MODIS active fire products were designated a provisional maturity status as of November 2000, following adjustments to the instrument. The provisional status means that the product is usable, although it has known problems and validation is ongoing.

Table 1
MODIS current and planned fire products

MODIS fire product	ESDT	Release date
Level 2 fire product	MOD14	February 2001
Rapid Response product	–	April 2001
Level 2G Daily Daytime Fire Product	MOD14GD	November 2000
Level 2D Daily Nighttime Fire Product	MOD14GN	November 2000
Level 3 Daily Fire Product	MOD14A1	November 2000
Level 3 8-Day Summary Fire Product	MOD14A2	August 2000
Global Daily Fire QA Browse Imagery	–	November 2000
1° Global Climate Modeling Grid Product (planned)	MOD14CMG1	Fall 2002
10-km Global Climate Modeling Grid Product (Planned)	MOD14CMG2	Fall 2002

The ESDT ("Earth Science Data Type") is a unique descriptor assigned to each MODIS product. As the rapid response and global browse fire products are not distributed from the ECS DAACs, no ESDTs are necessary for these products.

3.1. The Level 2 fire product (MOD14)

This is the most basic fire product in which active fires and other thermal anomalies, such as volcanoes, are identified. The Level 2 product is defined in the MODIS orbit geometry covering an area of approximately 2340 × 2030 km in the across- and along-track directions, respectively. It is used to generate all of the higher-level fire products, and contains the following components: (1) an active fire mask that flags fires and other relevant pixels (e.g. cloud); (2) a pixel-level QA image that includes 19 bits of QA information about each pixel; (3) a fire pixel table which provides 16 separate pieces of radiometric and internal-algorithm information about each fire pixel detected within a granule; (4) extensive mandatory and product-specific metadata. Product specific metadata within the Level 2 fire product includes the number of cloud, water, nonfire, fire, unknown, and other pixels occurring within a granule to simplify identification of granules containing fire activity. More detail about these fields is provided in the MOD14 file specification (ftp://modis-xl.gsfc.nasa.gov/pub/stig_temp/mlinda/www/LatestFilespecs/).

3.2. The daytime and nighttime Level 2G fire products (MOD14GD/MOD14GN)

The Level 2 active fire products sensed over a 12-h period data are binned without resampling into an intermediate data format referred to as Level 2G (Wolfe, Roy, & Vermote, 1998). The Level 2G format provides a convenient geocoded data structure for storing granules and enables flexibility for subsequent temporal compositing and data projection.

3.3. The daily and 8-day composited Level 3 fire products (MOD14A1/MOD14A2)

The MODIS daily and 8-day Level 3 fire products are tile-based products, with each product file spanning one of the 460 MODIS tiles, of which 326 contain land pixels. The product is a 1-km gridded composite of fire pixels detected in each grid cell over 1–8 days which make up the compositing periods. The 8-day composite represents the maximum value of the individual Level 2 pixels that fell into each 1-km grid cell over the 8-day compositing period.

3.4. Fire global browse product

Global browse images of the MODIS active fire product are generated on a daily basis at 5- and 20-km spatial resolution as Joint Photographic Experts Group (JPEG) images (Fig. 1). These products show the global distribution of fires for each day and have been useful for preliminary QA, allowing easy identification of potential problems such

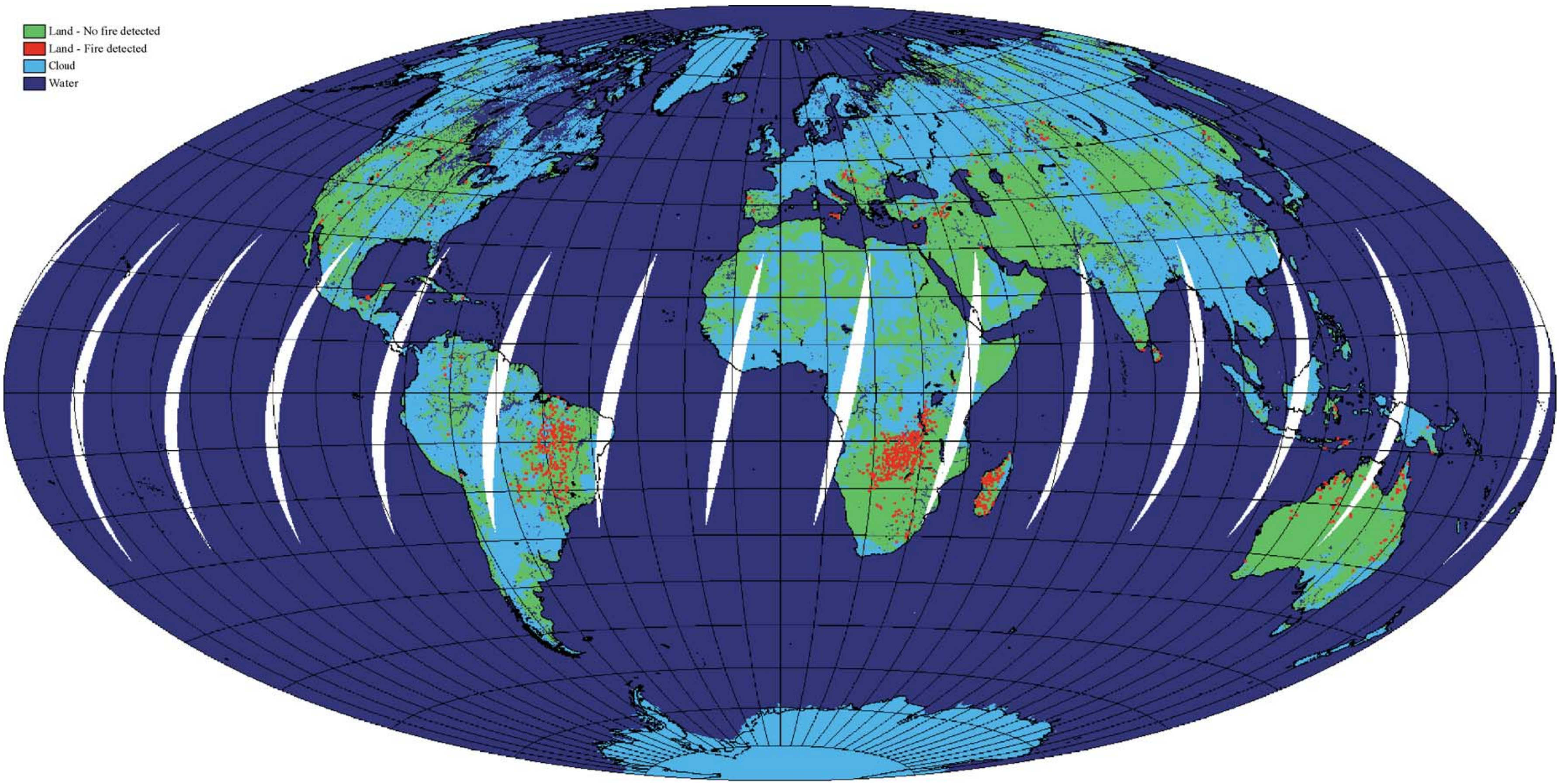

Fig. 1. Daily 20-km global browse image of the MODIS active fire product for 4 September 2001.

as excessive false alarms in a particular region. The browse product provides a convenient tool for quickly assessing areas and changes in fire activity. The browse products for all MODIS land products are available from the MODIS Land Global Browse web site (http://modland.nascom.nasa.gov/browse/).

3.5. The MODIS Rapid Response fire product

The MODIS Rapid Response System was developed in response to the need, articulated in particular by the fire community, for MODIS fire data shortly after acquisition. When the standard production system is operating nominally, the MODIS Level 2 and 3 data production will run approximately 7 days behind the current acquisition date. For some applications, such as fire management, the standard MODIS products are therefore of limited utility. During the large fires in Montana in 2000, there was an interest from the US Forest Service to obtain data within a few hours of acquisition to support strategic fire management. In April 2001, building on experience gained with the Land 250 m Distribution System (Justice et al., 2000), the Rapid Response System was initiated and is providing MODIS fire data and imagery (http://rapidfire.sci.gsfc.nasa.gov/) to the USFS Remote Sensing Applications Center in Salt Lake City (http://www.fs.fed.us/eng/rsac/) and the National Interagency Fire Center in Boise Idaho (http://www.nifc.gov/firemaps.html), through the University of Maryland Department of Geography (http://rapidresponse.umd.edu/). The MODIS Rapid Response System takes data directly from the EDOS data feed to NOAA at the NASA Goddard Space Flight Center and generates a Level 1B data product using the International MODIS/AIRS Processing Package (IMAPP) software provided by the University of Wisconsin (http://cimss.ssec.wisc.edu/~gumley/IMAPP/IMAPP.html). The MODIS fire algorithm is applied to the data. Images are then generated, superimposing the 1-km active fires on the 250-m corrected reflectance product for the same acquisition and made available over the World Wide Web (Fig. 2). Combining the two products provides a geographic context to the fire locations.

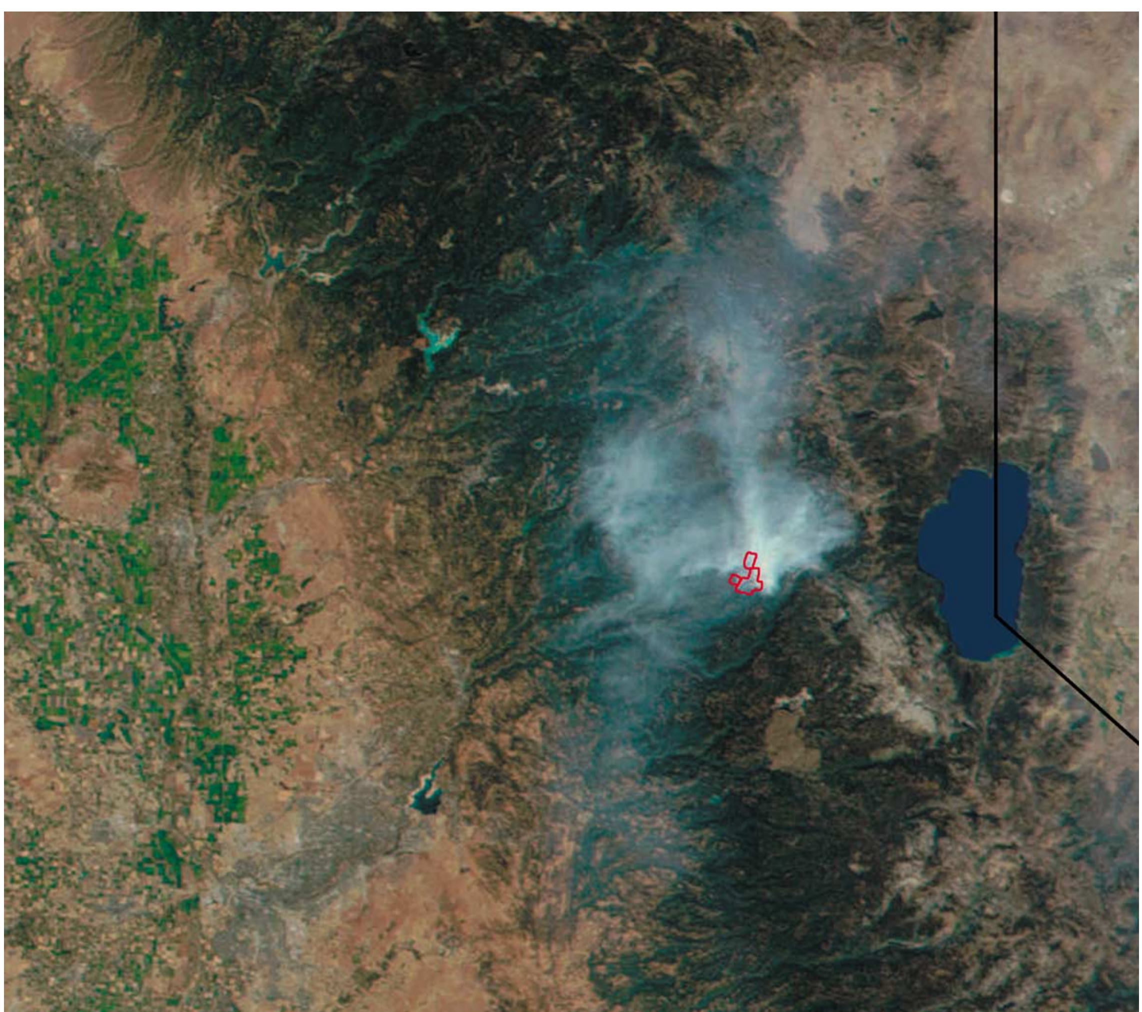

Fig. 2. Star fire near Lake Tahoe, California on 27 August 2001, 19:22 UTC. Pixels containing active fires, outlined in red, are superimposed on corrected true-color reflectances.

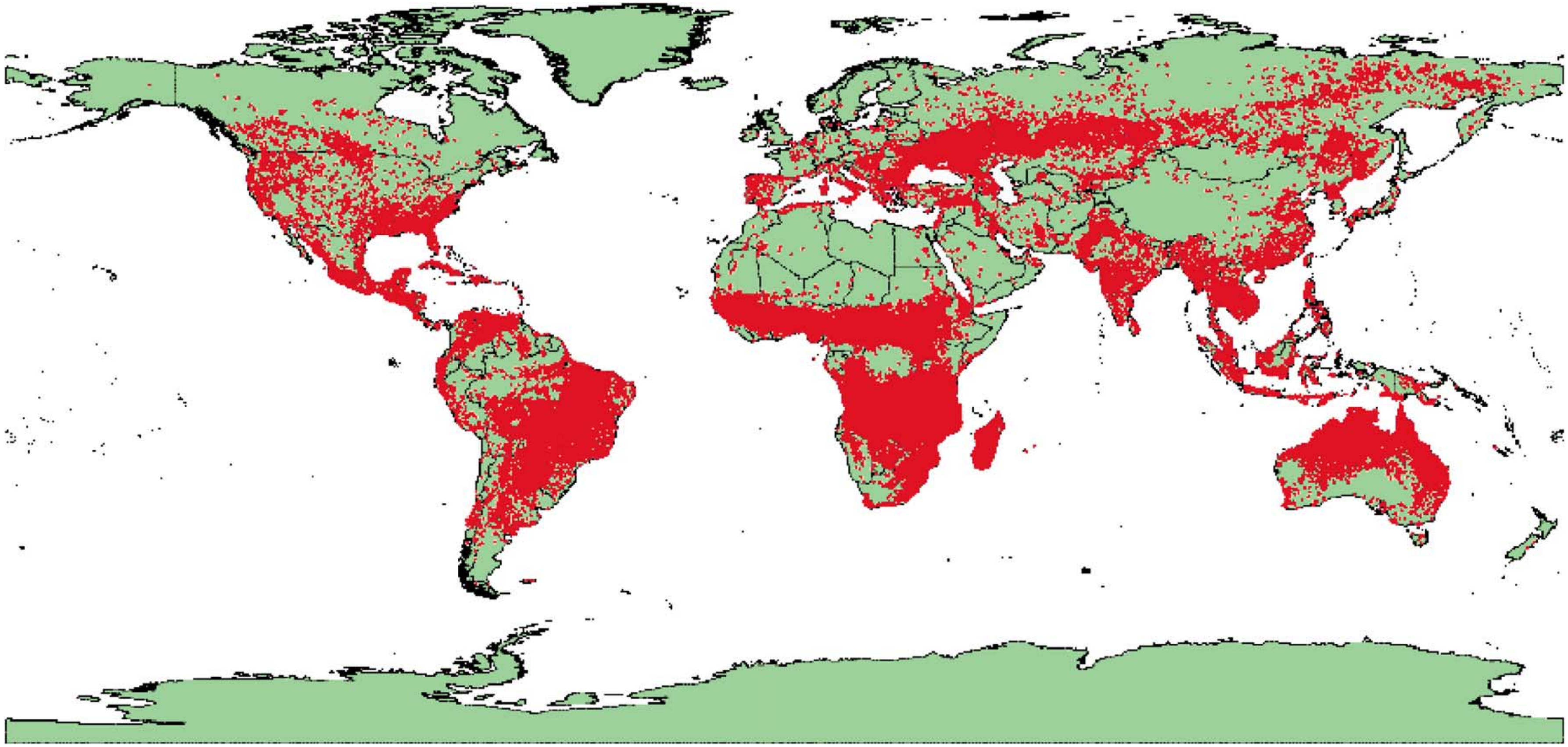

Fig. 3. Global cumulative active fire detections (23 April 2001 to 25 February 2002) from the MODIS Land Rapid Response System. Each red dot represents a single 1-km MODIS active fire pixel detected during the time period.

Daily distributions of active fire at 1 km are made available within 2–4 h of acquisition. Active fire locations are sent to a server for FTP distribution to a number of operational fire and forest monitoring organizations around the world.

This international outreach activity, providing improved data access, is being undertaken in the framework of the Global Observation of Forest Cover/Global Observation of Land Dynamics (GOFC/GOLD) Program (Ahern et al., 2001; http://www.gofc.org). Fig. 3 shows the global distribution of MODIS fire counts from April to February 2001. At the University of Maryland, the MODIS fire locations are also made available for different regions on a map server combined with interactively selectable map layers (http://firemaps.geog.umd.edu) using ArcIMS (Fig. 4).

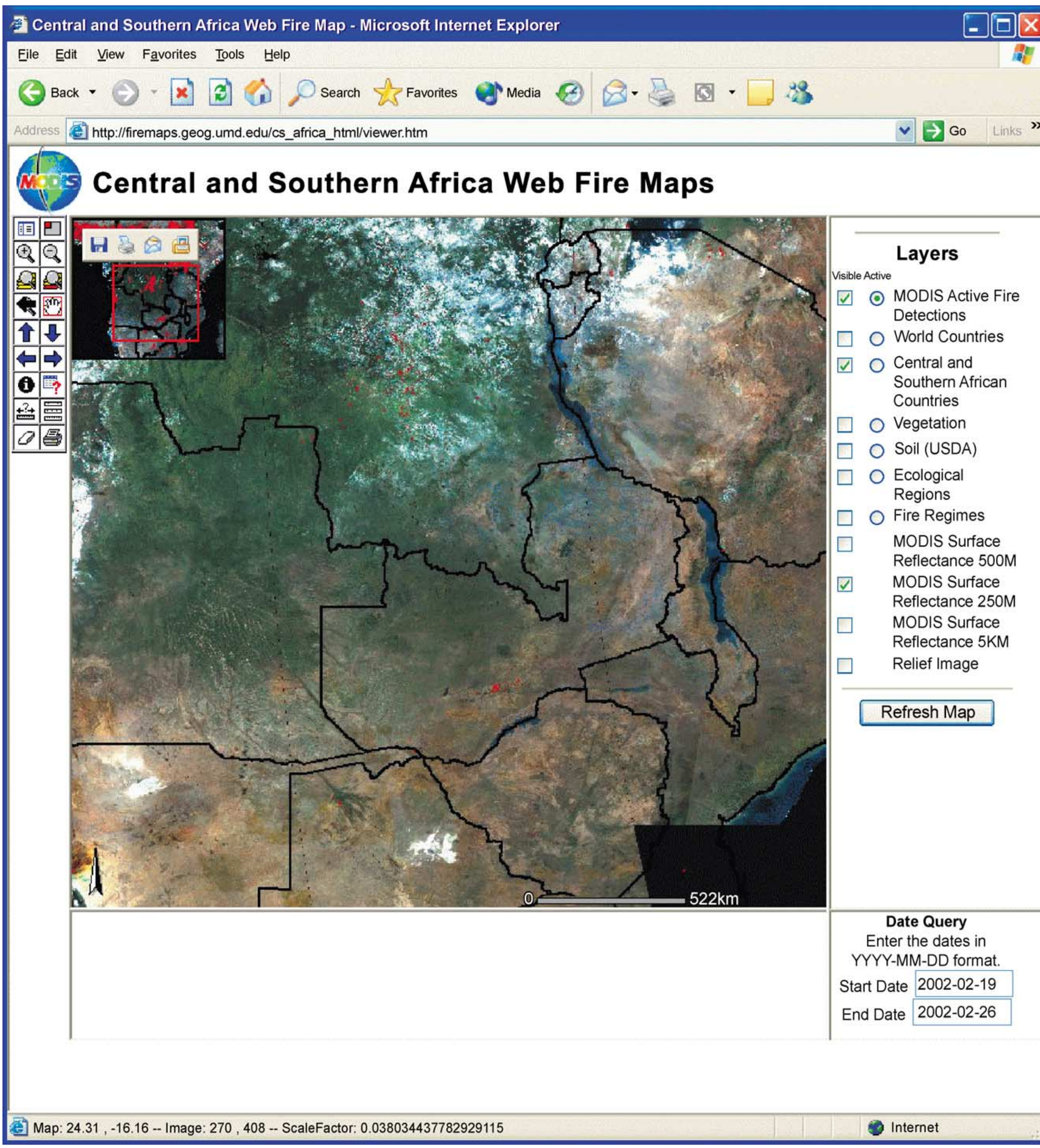

Fig. 4. Central and southern Africa Web Fire Maps site (http://firemaps.geog.umd.edu). The image shows MODIS active fire detections produced by the MODIS Land Rapid Response System overlaid on MODIS 250-m surface reflectance data in southern Africa.

4. Product quality assessment

4.1. Quality assessment activities

During the first several months following launch, detailed product quality assurance activities were applied to the MODIS fire products. These activities included daily inspection of global browse imagery, automated inspection of selected Level 2 product granules, and detailed examination of individual L1B orbit granules and the corresponding fire product. This was appropriate given the relative immaturity of both the 1B data and the higher-level derived fire products. However, following revisions to the algorithm, corrections to the production code made during 2000, and the substantial improvement in data quality in November 2000, such an intensive QA effort became unnecessary. Current QA activities consist of periodic inspection of the active fire global browse and Rapid Response products and investigation of the granules follows using one or more of the other methods discussed above.

4.2. Instrument performance and fire detection

The instrument performance has had a direct effect on the quality of the fire products. An ongoing issue affecting the MODIS active fire product is the calibration of channel 21, the principal fire band. The pre-launch saturation requirement for this band was 500 K. However, pre-launch testing only involved temperatures up to 340 K, which is 3.5% of the channel's full radiance. Attempts will be made to use observations of the moon and published mid-infrared lunar radiances for in-orbit calibration. The actual saturation level of channel 21 remains unknown and cannot be assumed to be linear.

4.2.1. Pre-November 2000

During the first 9 months of operation, the MODIS AM instrument suffered from several unexpected hardware problems that adversely affected all of the MODIS fire products. In setting the focal plane operational biases to reduce unexpected electronic crosstalk between several of the 500-m and 1-km bands, some detectors were rendered inoperable or otherwise unusable. An unintended consequence was the introduction of large, square artifacts adjacent to fires or high contrast areas and aligned with the scan and track directions. An example is shown in Fig. 5. Overall, these problems degraded the fire product by reducing the ability to detect both small (or cool) and large (or intense) fires in the contextual portions of the algorithm, and, on rare occasions, producing "bleeding" of the active fire front into neighboring nonfire pixels. The most obvious artifact evident in the Level 2 fire product was detector striping. To some extent, the striping propagated to the higher-level fire products. In the Level 3 daily product, striping was most evident but far less so in the 8-day summary due to the compositing method used in making this product.

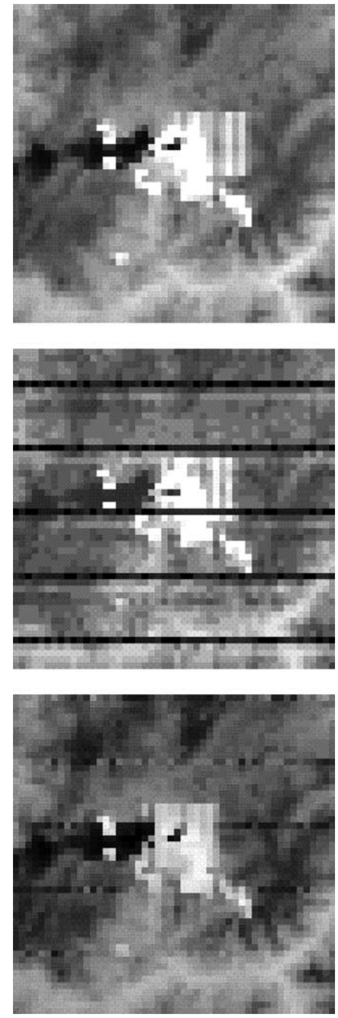

Fig. 5. MODIS channel 20 (top), 21 (center), and 22 (bottom) images of a large active fire in Montana, USA, acquired 30 July 2000. These images reflect the state of the three MODIS channel prior to the switch to B-side electronics in November 2000. A large square artifact induced by mid-IR focal plane crosstalk near the center of each image is evident in all channels; malfunctioning detectors are also apparent in channels 21 and 22.

In early November 2000 (Julian day 305), following a switch to the redundant "B-side" electronics and a change in the focal plane biases, the quality of the mid-IR channels used for fire detection improved significantly. Aside from a problem with the calibration of the ninth detector in channel 21, the problems described previously were largely eliminated. Therefore, for most applications and in particular for time-series analysis involving fire pixel counts, the use of the MODIS fire product generated from data acquired prior to early November 2000 is strongly discouraged.

Since November 2000, the MODIS fire products have exhibited some minor problems. In particular, a significant number of fires were missed due to the very conservative nature of the MODIS Cloud Mask product (MOD35) which was used for cloud screening in the fire code. This resulted in some of the active fires and other surface features being classified as cloud. In early 2001, an internal cloud masking

Table 2
Scene information for the MODIS to ASTER comparison

Scene ID	# of MODIS pixels	# of MODIS fire pixels (MOD14 = 1)	# of MODIS pixels containing ASTER fire pixels	MODIS granule ID	ASTER granule ID
A	3881	5	19	A2000328.0920.002.2001008214203	pg-PR1B0000-2000120602_037_001
B	3923	13	52	A2000328.0920.002.2001008214203	pg-PR1B0000-2000120602_039_001
C	3890	14	46	A2000328.0920.002.2001008214203	pg-PR1B0000-2000120602_108_001
D	3865	4	14	A2000328.0925.002.2001008214916	pg-PR1B0000-2000120602_121_001

procedure was incorporated into the production code to alleviate this problem. This procedure will remain in use until improvements are made to the cloud mask product. A complete summary of all known problems associated with the fire products can be found on the MODLAND Quality Assurance (QA) web site (http://landdb1.nascom.nasa.gov/QA_WWW/qahome.html).

4.2.2. Post-July 2001

On 15 June 2001, the MODIS instrument was shut down in response to a problem with the B-side electronics power supply. On 2 July 2001, normal operations were restored using the A-side electronics and associated power supply. The decision was made to stay with the A-side. Although the overall quality of MODIS data following this event is good, significant striping is currently present in channels 21 and 22, resulting in some degradation of the fire products.

4.3. Current algorithm performance

The detection algorithm is currently functioning reasonably well following several post-launch revisions. Some sensitivity to relatively small yet obvious fires has been sacrificed to reduce persistent false detections occurring in regions of hot, reflective exposed soil. Nevertheless, some of these persistent false alarms remain, particularly in northern Ethiopia. Not unexpectedly, most are caused by the algorithm's absolute threshold tests. To restore detection of these small fires and reduce the persistent false alarms, a major algorithm revision is under development and will be incorporated in the operational processing system in mid-2002 (Giglio, Descloitres, Justice, & Kaufman, in preparation).

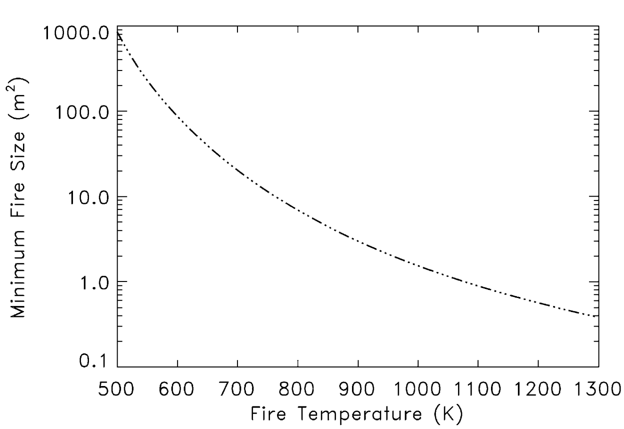

Fig. 6. Minimum fire size required to saturate ASTER band 9 as a function of fire temperature under typical daytime conditions.

5. MODIS fire validation

Validation requires an independent source with which to compare the MODIS product. This source should have a known level of accuracy and the comparison should be done at a globally representative set of sites (Justice et al., 2000). MODIS fire product validation is being undertaken through a series of ongoing collaborative intercomparisons with other fire products and with a global sample of ASTER data. In addition, a number of field-based validation activities have been established in collaboration with international fire groups, through the GOFC/GOLD-Fire program and in collaboration with the Land Product Validation (LPV) subgroup of the Calibration and Validation Working Group of the Committee on Earth Observation Satellites (CEOS) (Morisette, Justice, Pereira, Grégoire, & Frost, 2001).

Fig. 7. Example of 1 km-MOD14 fire pixels (white squares) over corresponding ASTER scene. Bright ASTER pixels are saturated pixels in the 2.43-μm channel and correspond to the flaming front of the fire. Also evident is an undetected fire to the lower left of the detected fire.

Conventional approaches to the validation of satellite-derived active fire products involve ground and aircraft measurements of prescribed burns and opportunistic aircraft measurements over wildfires. These approaches have heretofore been extremely difficult due to the dynamic and transient nature of active fires, aircraft expense, and practical limitations of coordinating cloud-free satellite overpasses with prescribed burns. However, simultaneous acquisition of independent high spatial resolution observations of fires is now possible for MODIS. The ASTER instrument, also on-board the Terra Platform, has 15 spectral bands from 0.5 to 10 μm at resolutions from 15 to 90 m (Yamaguchi, Kahle, Tsu, Kawakami, & Pniel, 1998). Using ASTER data, we are able to obtain a global sample of high-resolution fire detection. These are then projected onto the coincident MODIS pixels for statistical comparison. Here we describe initial validation results based on four ASTER scenes falling within two MODIS granules over southern Africa (Table 2). MODIS fire product validation is ongoing and will build on the type of MODIS/ASTER comparison described here, at more sites covering each continent and major biome.

The ASTER data first were converted to a high-resolution fire map with a simple threshold. Fig. 6 shows that fires less than 1000 m^2 will saturate the ASTER band 9 (2.4 μm), and that a simple saturation threshold for cloud-free scenes can be used to identify fires in ASTER data. On these high-resolution fire maps, fire pixels within 150 m of each other were grouped together to form a single fire "cluster". The ASTER fire clusters and MODIS pixels were then associated by mapping the 1 by 1 km square of each MODIS pixels onto the ASTER data (Fig. 7). A registration accuracy of better than 300 m can be estimated according to the geolocation accuracy of both instruments; less than 100 m for ASTER (Fujisada, Iwasaki, & Hara, 2001) and less than 200 m for MODIS (Wolfe et al., 2002, this issue).

For each MODIS pixel, the ASTER data within that MODIS pixel were summarized using several variables, in

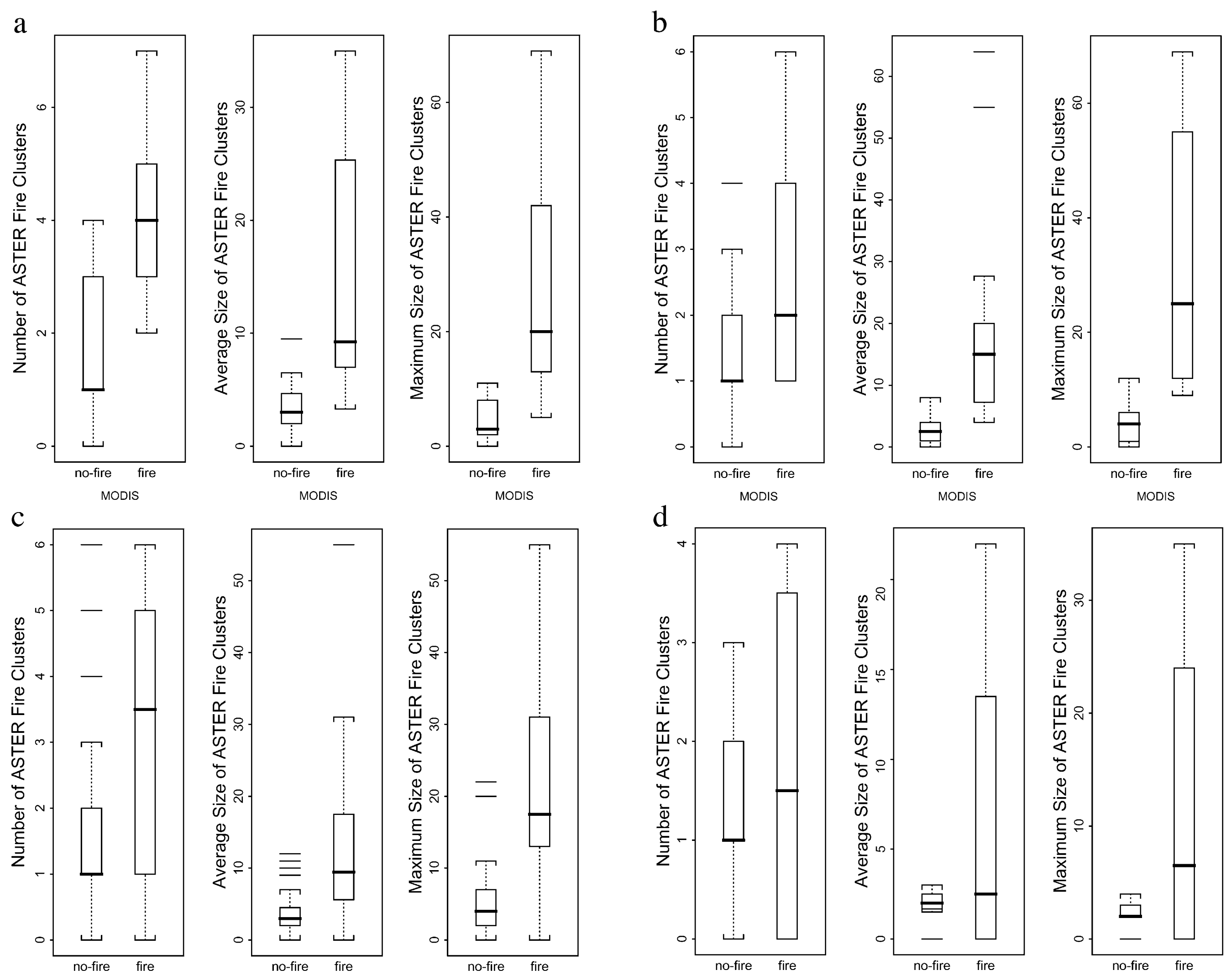

Fig. 8. (a–d) Box plot of ASTER-derived variables for MOD14 = no-fire (0) or fire (1) for scenes A–D, respectively.

particular: (1) the number of ASTER clusters within the MODIS pixel, (2) the average size of those clusters, and (3) the maximum size of the ASTER fire clusters. The distributions of these variables were then separated into two groups based on whether their corresponding MODIS pixel was classified as *no-fire* or *fire*. The distributions are shown as box plots in Fig. 8. The distributions for each of the three ASTER-derived variables are higher for those pixels classified by MOD14 as fire. This indicates that the MOD14 product behaves appropriately with respect to the observed ASTER data. That is, more and larger fire clusters are associated with those MOD14 pixels classified as fire.

Fig. 9 shows a scatter plot of two of the ASTER-derived variables and the MODIS fire products from the four locations. The *X*- and *Y*-axis show the number of ASTER fire clusters vs. the maximum size of ASTER clusters for a 1-km area corresponding to a MODIS pixel. The MODIS fire product is represented on the scatter plot by the size of the circle, where small circles represent no-fire and larger circles represent fire. We see the general relationship between the MODIS and ASTER-derived variables is as expected. Overall, the MODIS fire pixels are associated with larger maximum cluster sizes and/or larger numbers of clusters. For scene A, there is a very clear division between the fire/no-fire pixels. The separation is less clear for scenes B and C, although the general relationship holds. The few (four) MOD14 fire pixels in scene D confuse the relationship. The large circles at the [0,0] point for scenes C and D indicate "commission errors" or "false-positives", where the MODIS pixel was classified as fire while none of the corresponding ASTER pixels were classified as fire (for scene D, there are two overlapping fire pixels at the [0,0] point).

General statements about the accuracy of the MOD14 product will require similar analyses on more scenes. The analysis presented here is only for data based on MODIS pixels assuming a square shape. Initial results for the line spread function (LSF, Kaufman, Justice et al., 1998) data sets were similar. While it is coincident in time, there are some characteristics of the ASTER instrument that imply some caution when comparing to MODIS. ASTER channel 9 at 2.43 μm corresponds to the nearest window sensitive to emissive radiation at typical fire temperatures. At this wavelength, daytime identification of smoldering fires may be problematic. ASTER channel 9, for example, can be saturated by high surface reflectance in addition to active fires. The detection threshold and accuracy of the ASTER fire detections have yet to be quantified. It should also be noted that the results will only be applicable for the center part of the MODIS swath and may not be representative of detection accuracies further off-nadir. The cross-track pointing capability of ASTER, designed to increase revisit time, needs to be explored for off-nadir fire evaluation. Also, further analysis is needed to test the sensitivity of the MODIS/ASTER comparisons and the choice of the distance

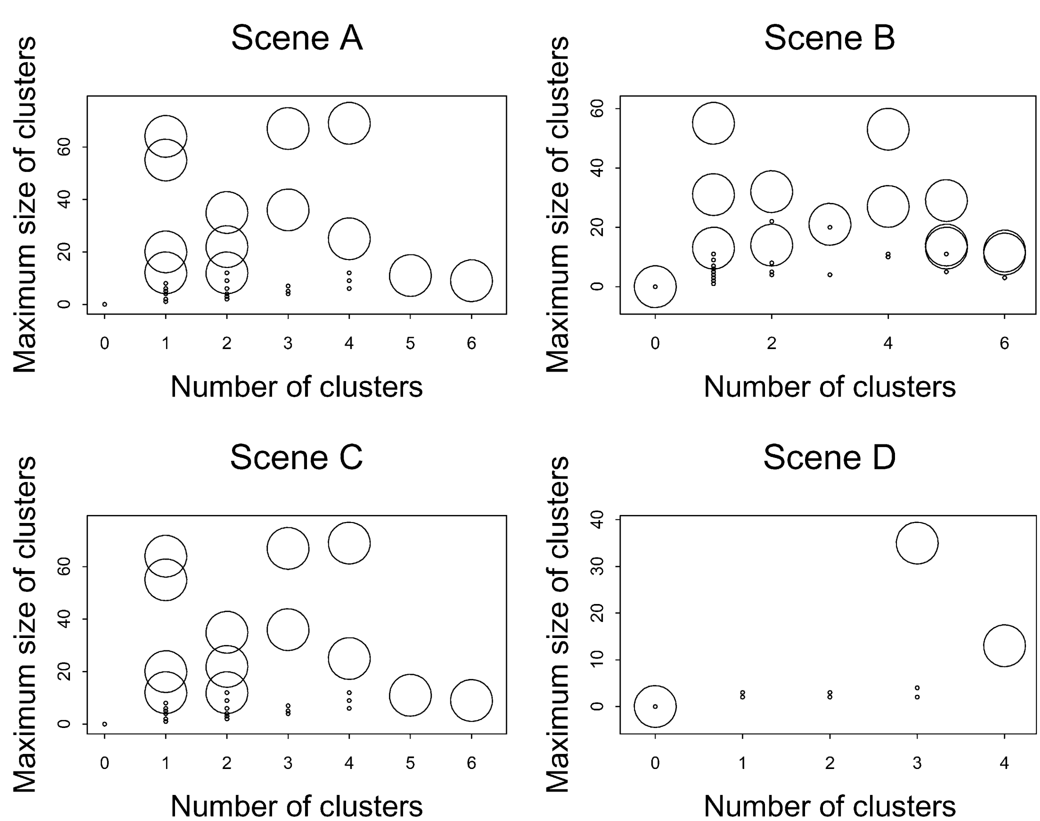

Fig. 9. Scatter plots of number of clusters vs. maximum size. Small circles indicate pixels where MOD14 = no-fire and larger circles where MOD14 = fire.

rule for clustering. A comparison using more ASTER scenes from different fire regimes around the world is underway.

6. Planned products

The MODIS fire team strategy has been to phase-in the various fire products. Starting with the Terra active fire products once the instrument was characterized, progressing to the burned area product as the geolocation accuracy of the system was refined, and then to generate a coarse-Climate Modeling fire product, as the fire algorithm becomes stable and the data system has the capacity to reprocess data and generate consistent time-series data sets.

The launch of the Aqua platform in 2002 will provide four fire observations per day. A preliminary analysis of TRMM VIRS observations indicates that there will be a significant improvement in our ability to detect fires as a function of the diurnal cycle of fire activity (Giglio et al., in preparation). TRMM has a highly inclined orbit, which covers the diurnal cycle over roughly a 28-day period (Giglio, Kendall, & Tucker, 2000). Figs. 10 and 11 were developed using TRMM observations for locations in southern Africa and the southern United States during July 2000; each shows fire frequency as a function of overpass time. Although preliminary, these early results demonstrate the strong variation in fire activity as a function of time-of-day, as previously shown from GOES (Prins & Menzel, 1992). The MODIS AM and PM overpass times are indicated in green and blue vertical lines, respectively. The performance of the Aqua MODIS instrument will need to be carefully evaluated following the launch to ensure that the instrument performance allows reliable fire detection, and that the combined product is consistent. Tracking two instruments and determining the combined product accuracy will require careful QA.

6.1. Monthly climate modeling grid fire products

This product will provide a monthly coarse-resolution statistical summary within 1° and 10 km grids and is planned for release in late 2002. Both products are primarily intended to facilitate the incorporation of the MODIS active fire products into global climate, transport and emissions models. As the climate modeling community is interested in stable time-series data, this product will be generated as part of the next full data reprocessing. The MODIS fire CMG products are described in more detail by Kaufman et al. (in press).

6.2. The MODIS burned area product

Reliable spatially explicit burned area data sets are required to feed the information needs of policy makers, the scientific community, and natural resource managers. For most fire regimes, the timing and spatial extent of burning cannot be estimated reliably from active fire detection, as the satellite may not overpass when burning occurs and because clouds may preclude active fire detection. A prototype MODIS burned area algorithm has been developed which maps the approximate day of burning at 500 m using multitemporal MODIS land surface reflectance data. In the current approach, a bi-directional reflectance model is inverted against multitemporal 500-m land surface reflectance observations to provide predicted reflectances and uncertainties for subsequent observations. Large discrepancies between predicted and measured values are attributed to change. The algorithm addresses the bi-directional reflec-

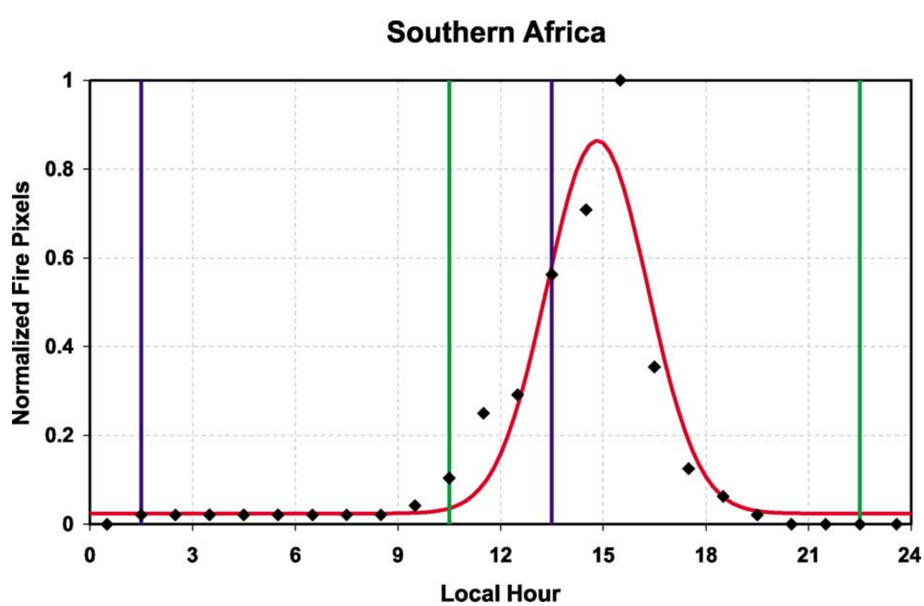

Fig. 10. Diurnal distribution of active fire pixels for southern Africa during July 2000. The red line is a Gaussian fit to the observations. Terra AM and PM overpass times are shown in the green and blue lines, respectively.

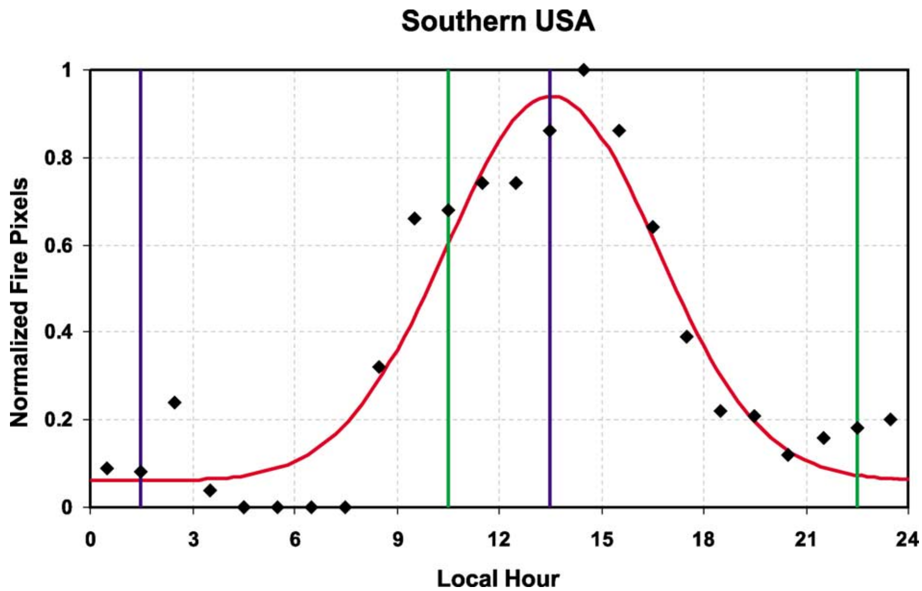

Fig. 11. Diurnal distribution of active fire pixels for the southern United States during July 2000. The red line is a Gaussian fit to the observations. Terra AM and PM overpass times are shown in the green and blue lines, respectively.

tance variations observed in MODIS data and enables the use of a statistical measure to detect change from a previously observed state. A temporal consistency constraint is used to differentiate between temporary changes considered as noise and persistent changes of interest. Details are provided in Roy et al. (2002, this issue). A computationally simpler algorithm that examines the temporal consistency of a time series of spectral vegetation index values in conjunction with the active fire product is also being developed. Recognizing the significant differences between regional fire regimes, the MODIS Fire Team is taking a regional approach to generation, testing, and validation of the MODIS burned area product. The Southern Africa Fires and Atmospheric Research Initiative (SAFARI 2000) was selected as the first regional test for the prototype MODIS burned area product. Product validation is being undertaken with southern African collaborators, who have strong interests in long-term fire information to support their research and operational agendas in resource management and environmental assessment. They are currently using Landsat ETM time-series burned area interpretations to quantify the accuracy of the regional MODIS burned area product at sites across southern Africa.

7. Burned area and fire emissions from African savannas: a pilot study

The Southern Africa Fires and Atmospheric Research Initiative (SAFARI) 2000 was selected as the context for the initial development and testing of a prototype MODIS burned area product (Roy et al., 2002, this issue). In the absence of a strong heritage for moderate resolution burned area mapping and the experimental nature of the algorithm, emphasis has been given to establishing a validation data set with which to evaluate the MODIS beta product. Landsat time-series burned area interpretations are being used to quantify the accuracy of the MODIS burned area product for African savannas. Newly burned areas mapped from two Landsat scenes acquired approximately one month apart are compared to the MODIS burned areas detected for the same period.

In addition to providing a means for MODIS validation, higher resolution Landsat burned area time-series enable us to further examine the spatial and temporal requirements for the MODIS burned area in order to improve the accuracy of the pyrogenic trace gas and particulate emissions estimates. This pilot study was undertaken as an input to the MODIS burned area development. So far, fire emission models have used as an input the total area burned within a fire season (Barbosa, Stroppiana, Gregoire, & Pereira, 1999; Scholes, Ward, & Justice, 1996). Korontzi, Justice, and Scholes (in press) demonstrated that relying on annual burned area estimates from remote sensing introduces errors in the quantification of pyrogenic emissions from savanna ecosystems and that among other data, multidate information on burned area is required to improve the accuracy of emissions estimates. In addition to the temporal requirements, we have initiated a parallel supporting activity to examine some of the spatial resolution requirements for the MODIS burned area satellite product.

The location selected for this pilot study was of a savanna and dambo grassland region, in Central Zambia (WRS #173069). The fire season in this region runs typically from May to October. Five Landsat MSS scenes spaced about a month apart and covering the 1989 fire season were digitized for their burned areas to assess the contribution of the monthly burning to the total pyrogenic emissions over the entire fire season and compare them with the total burned area approach to estimate emissions. Furthermore, the contribution of burn scars smaller than 1 km^2 to the monthly and total emissions was calculated.

From Fig. 12, it can be seen that there was more than a doubling in CO_2 from June to July. After this time, CO_2 emissions reached a plateau. This increase in CO_2 as the dry season progressed was primarily due to the higher combustion completeness as the season progresses, and to a lesser extent due to the small increase of area burned in July as compared to June. The temporal distribution of area burned was 20% May–June, 24% June–July, 24% July–August, and 32% August–September. At the same time, emission factors did not vary significantly from July to September (Korontzi et al., in press), which in combination with the almost even distribution of area burned could explain the similarity in CO_2 emissions from July through September.

On the other hand, emissions of products of incomplete combustion (PIC) exhibited an almost opposite trend to CO_2 (Fig. 13). This was somewhat anticipated, as the moister vegetation burning at the beginning of the dry season produces more PIC relative to later in the season. PIC emissions reached a peak in July and then dropped substantially at the latter part of the fire season. This was attributed to the fact that fuel consumption was much higher in July than in June (Hoffa et al., 1999; Korontzi et al., in press). It could be explained if one considers that the fuel is wetter at the beginning of the season, and as it dries out, more burns. The PIC emission factors in July, even though smaller than in June, were still high enough to drive up emissions. What is interesting to note, though, is the fact that the June PIC emissions were similar to or slightly higher than those in the late dry season. Towards the end of the season even though fuel consumption was higher, due to the drying out of the biomass fuel, the PIC emission factors were much lower and resulted therefore in lower emissions. (For the values of the emission factors used refer to Korontzi et al., in press). Using the total annual burned area method to estimate emissions resulted in an underestimation of PIC. For example, CH_4 emissions were underestimated by a factor of 2.8.

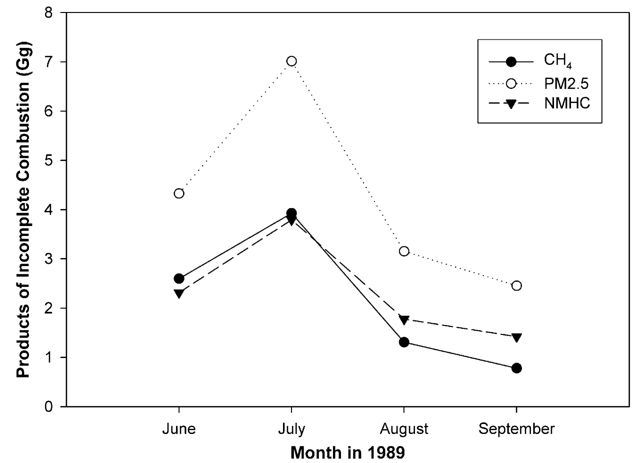

Fig. 13. Time series of pyrogenic CH_4, PM2.5, and NMHC emissions.

This simulation study indicates that assessment of the intraseasonal variability of the burning activity parameters, such as burned area, biomass burned, and emission factors, is required to calculate emissions and account for the complexity of fire patterns and their controlling variables at different times of the fire season in savanna ecosystems. This study would indicate the requirement for at least a monthly estimation of burned area from MODIS in savanna systems.

To facilitate the determination of the MODIS burned area spatial requirements for accurate pyrogenic emissions modeling in savanna ecosystems, we used the same Landsat time series to assess whether a burned area product of 1000-m resolution was satisfactory or whether a higher resolution would be more desirable. As seen in Fig. 14, scars smaller

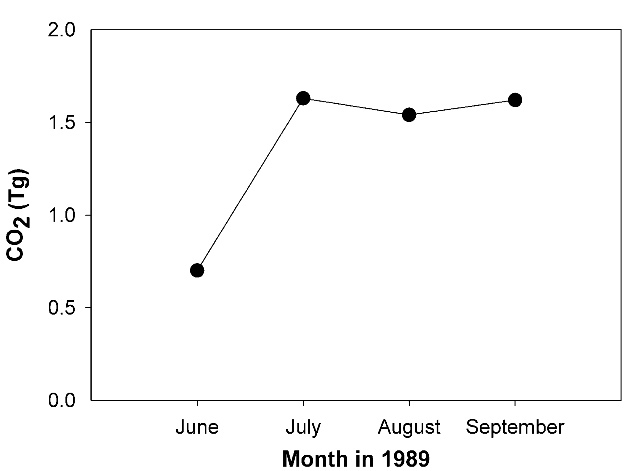

Fig. 12. Time series of pyrogenic CO_2 emissions.

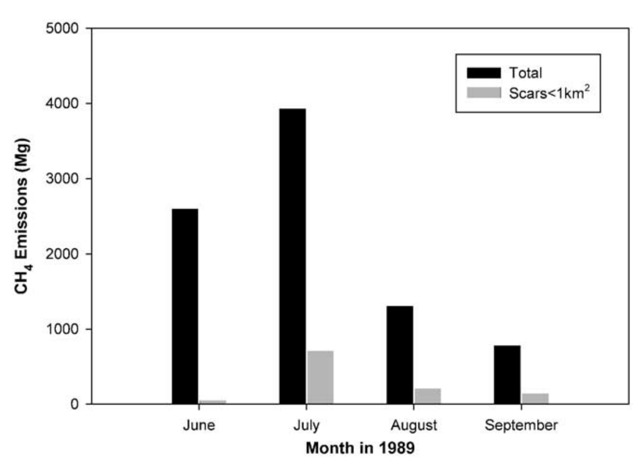

Fig. 14. Contribution of fire scars smaller than 1 km^2 to total CH_4.

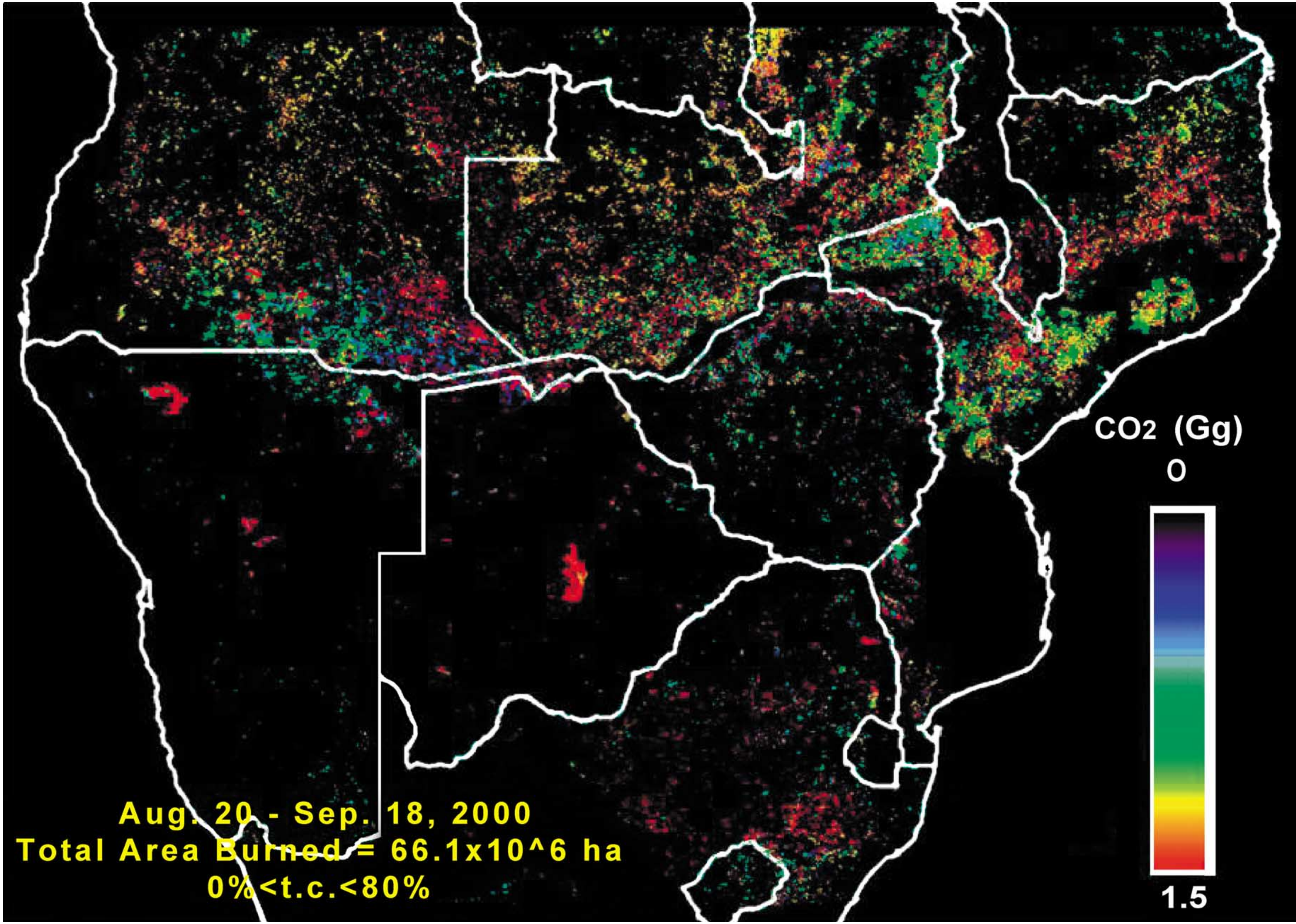

Fig. 15. Modeled CO_2 emissions estimates for 1 month of the 2000 southern Africa fire season.

than 1 km^2 contributed 16–19% of the monthly CH_4 emissions. These numbers, though, could be slightly larger considering that there are additional cases in which scars smaller than 1 km^2 might go undetected using Landsat due to vegetation regrowth between dates or removal of the char by wind. It should also be noted that the July CH_4 emissions from scars smaller than 1 km^2 were almost equal to the total CH_4 emissions in September.

This study was for one location and additional studies are needed to evaluate the contribution of smaller scars (< 1 km^2) to regional emissions budgets, but it appears that they might be significant, and that a higher than 1000-m spatial resolution is preferable for regional burned area products. The highest candidate resolution for a MODIS burned area product is 250 m. However, 250-m data present problems in terms of data volumes (Justice et al., 2002, this issue). A 500-m resolution may provide a compromising solution, but clearly further analysis is needed.

7.1. Regional pyrogenic emissions over southern Africa

A prototype emissions model was developed for southern Africa using an experimental MODIS burned area time-series data set developed by Roy et al. (2002, this issue). The model is documented in detail by Korontzi, Justice, Roy, and Dowty (submitted for publication). A dynamic fuel load model that estimates Net Primary Productivity (NPP) and uses empirical relationships to allocate fuel load and types, is also used at a high-resolution time scale (Hély et al., submitted for publication). The seasonality of emission factors for trace gases and aerosols is modeled to account for variations in the vegetation moisture content during the fire season and the resulting effects on the type and amounts of the emissions produced. In addition, significantly different algorithms, for grassland and woodland savannas, are used to relate the emission factors to the combustion efficiency and the fuel type mixture. The University of Maryland percent tree cover (TC) product at 1 km (Hansen et al., 2002, this issue) was used to stratify grasslands with $TC < 10\%$ and woodlands with $10\% < TC < 80\%$. In addition to emission factors, combustion completeness also varies within the fire season and is related to the fuel mixture.

The modeled estimates for one month towards the end of the 2000 fire season, during the SAFARI 2000 dry season campaign, are about 305 Tg CO_2 (Fig. 15), 15.6 Tg of CO, 0.4 Tg of nonmethane hydrocarbons, 0.5 Tg of CH_4, and 0.6 Tg of particulates with diameter less than 2.5 μm. Based on 1992–1993 AVHRR data (Stroppiana, Brivio, & Gregoire, 2000), the month of mid-August to mid-September accounts for approximately 20% of the total emissions in the fire season in southern Africa. Extrapolating our modeled estimates to the whole of the fire season would bring the total CO_2 emissions to 1525 Tg of CO_2. This number is about five times higher than the average estimate of 324 Tg generated by Scholes et al. (1996). However, a direct comparison is not possible since the 2000 fire season followed a very wet growing season, which resulted in a noticeable increase in fire events especially for the shrub and grassland areas of Namibia and Botswana (Anyamba, Justice, & Tucker, submitted for publication). Research is underway to assess the accuracy of this modeling approach, address its limitations and potential refinements.

8. MODIS fire: the next steps

There are a number of near-term priorities for the MODIS Fire Group. A high priority involves advancing from the generation of provisional data to validated fire data products. Validated products require a quantitative assessment and reporting of global product accuracy in a way that is useful to the data users. For the active fire product, this will include analyzing a broader sample of coincident ASTER data, taken from a range of fire regimes and establishing accuracy statistics that can guide the user community with product utilization. The Fire Group is also preparing for the launch of Aqua which will provide two additional fire observations per day, at 02:00 and 14:00. Association with the additional fire observations will be the task of establishing the relationship between the two instrument calibrations and the consistency of the product developed from two instruments. This will require careful post-launch characterization of Aqua MODIS and the intercalibration of the MODIS instruments.

Although there is an unprecedented amount of information on the Internet associated with the MODIS instrument performance and products, there remains a need for the Fire Group to help the broader user community to utilize the MODIS fire products and to work with users to better understand and refine the MODIS product. There is a growing interest from the fire management community in utilizing MODIS data but with an emphasis on timely data access and ease of use. The cooperation between the Fire Rapid Response Group and the US Forest Service has provided an initial interaction, which needs to be strengthened and broadened to other users (Sohlberg, Descloitres, & Bobbe, 2001). To facilitate and increase data use, there is the need to tailor MODIS fire products to user needs. The Fire Rapid Response System provides an operational prototype of a data delivery system allowing easy browse and data download. For natural resource management, satellite data are often used in conjunction with other data. Providing data products, which are compatible within a GIS framework, will make MODIS data readily usable. The Fire Group will continue to experiment with serving MODIS fire data and images using Internet GIS.

The current algorithm builds on the heritage approach developed for the NOAA AVHRR and TRMM VIRS. An experimental daytime algorithm for fire detection has been developed within the MODLAND group, taking advantage of the improved spectral capabilities of MODIS (Petitcolin & Vermote, 2002, this issue). The approach uses middle-infrared reflectance and permits a direct per-pixel identification of fires, rather than a contextual approach. The contextual approach makes an assumption that the surrounding pixels have the same brightness temperature as the fire pixel, which is problematic in highly heterogeneous areas. The next step is to compare the performance of the standard and experimental algorithm over a broad range of fire regimes.

While we are in the process of evaluating the performance of MODIS for fire detection, the design for the next-generation moderate resolution sensor is underway. The National Polar Orbiting Environmental Satellite System (NPOESS) Preparatory Project (NPP) will include the Visible/Infrared Imager/Radiometer Suite (VIIRS), which will replace the AVHRR as the operational moderate resolution imager and include several of the characteristics of MODIS (Townshend & Justice, 2002, this issue). An intriguing aspect of the proposed VIIRS active fire product is that instantaneous estimates of average fire temperature and area must be provided (NPOESS Integrated Program Office, 1999). Results of a recent analysis by Giglio and Kendall (2001) indicate that this will be a formidable challenge, especially given the 750-m nadir resolution of the VIIRS fire bands. Unfortunately, monitoring fires was not considered as a high-priority requirement for NPOESS (Jacobowitz, 1997), and the current instrument specification reflects this fact. The principal fire bands planned for the VIIRS include a very high saturation 4-μm channel and a low-saturation (~ 340 K) 11-μm channel. Theoretical calculations and analysis of MODIS data show that, when observing large active fires, the 11-μm channel as planned will saturate too frequently and thus significantly hamper the ability to retrieve fire characteristics of temperature and area. Methods for working around this limitation are actively being pursued. At this time, however, the primary proposal for bypassing this instrument limitation may introduce nontrivial biases in the resulting area and temperature estimates (Giglio & Justice, submitted for publication).

There are a number of satellite systems being used for monitoring fires, supported by different space agencies. These, together with ground-based fire-monitoring systems, provide the foundation for an international global fire observing system (Ahern et al., 2001). To realize this goal, there are a number of areas that will require international coordination and cooperation. The GOFC/GOLD-Fire program has been established to address this need for international coordination, with an emphasis on better articulating user information requirements and working with the fire data producers to meet those needs (Justice & Korontzi, 2001). GOFC/GOLD is developing observatories for carbon studies, ecosystem assessment, and natural resource management, each of which require fire observations. The MODIS Fire Team is playing an active role in this international program. Among the priorities for GOFC/GOLD-Fire are advocacy for the next generation of operational satellites to include fire monitoring capabilities (both polar orbiting and geostationary), coordination and cost sharing to develop the infrastructure needed for global fire product validation, improved access to current data sets, and increased involvement of regional networks of fire scientists and managers to evaluate and utilize the data. As part of this international program, the MODIS group has been providing Rapid Response data to international partners and proposing standards for other systems to provide similar access to fire location data via the Internet, allowing users to merge fire data from multiple instruments. Fig. 16 shows an example of MODIS, DMSP, and TRMM data merged in a GIS framework. The MODIS Fire Team is also working with GOFC/GOLD regional networks and the CEOS LPV subgroup to develop product validation protocols and evaluating MODIS fire data in different regions.

With the above tasks ahead of the MODIS Fire Team, the next phase of MODIS fire research will require considerable effort. A balance will be needed between improving and validating the Aqua products, combining the Terra and Aqua observations, and working with the user community to refine the products and increase utilization of the data.

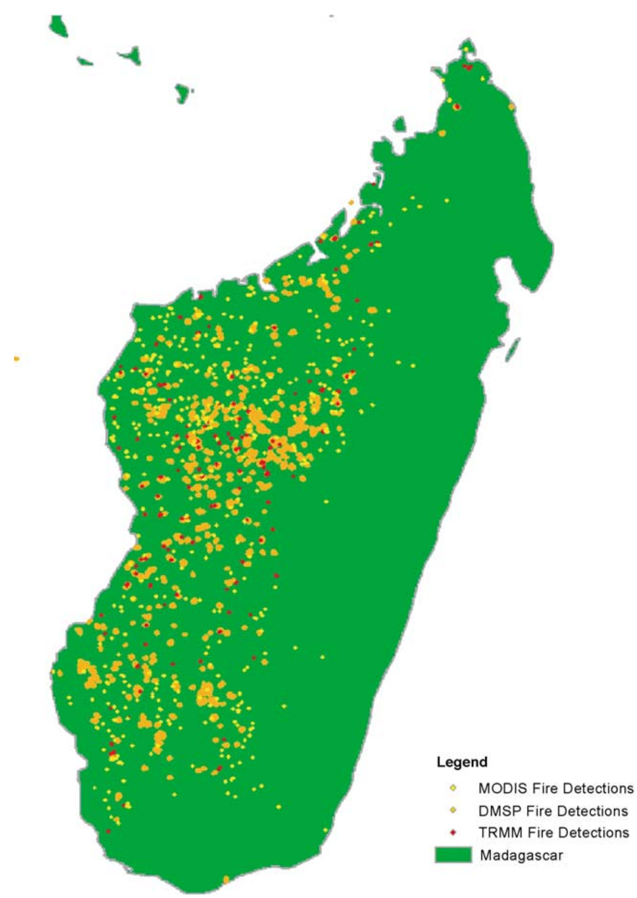

Fig. 16. Active fire detection over Madagascar from three satellite instruments from 1–4 August, 2001. MODIS active fire detections are from the MODIS Land Rapid Response System. DMSP fire detections are courtesy of NOAA National Geophysical Data Center.

Acknowledgements

We thank Pete Dowty and Christelle Hely at the University of Virginia for providing the fuel load model output within the context of the SAFARI 2000 project. We thank Melissa S. Crisologo for assistance with many of the figures, and four reviewers for many useful comments and suggestions. This work was supported by MODIS, largely through NASA Contract NAG 526759.

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