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The MODIS Land product quality assessment approach

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Abstract

The correct interpretation of scientific information from global, long-term series of remote sensing products requires the ability to discriminate between product artifacts and changes in the Earth processes being monitored. A suite of global land surface products is made from Moderate Resolution Imaging Spectroradiometer (MODIS) instrument data. Quality assessment (QA) is an integral part of this production chain and focuses on evaluating and documenting the scientific quality of the products with respect to their intended performance. This paper describes the QA approach adopted by the MODIS Land (MODLAND) Science Team and coordinated by the MODIS Land Data Operational Product Evaluation (LDOPE) facility. The described methodology represents a new approach for assessing and ensuring the performance of land remote sensing products that are generated on a systematic basis.

1. Introduction

Space agencies worldwide have several moderate and coarse spatial resolution sensing systems in orbit (e.g., MODIS, Tropical Rainfall Measuring Mission, Sea-viewing Wide Field-of-view Sensor) and planned for launch (e.g., Advanced Along Track Scanning Radiometer, Global Land Imager, National Polar-orbiting Operational Environmental Satellite System Preparatory Project) to provide geophysical and biophysical data on a global, systematic basis. The products generated from these data will provide long-term records of the atmospheric, terrestrial and marine ecosystems and will be used to develop a comprehensive understanding of Earth system functioning (Kaufman, Herring, Ranson, & Collatz, 1998). The MODIS Land (MODLAND) Science Team (ST) is funded by the National Aeronautics and Space Administration (NASA) to develop the science algorithms and processing software used to generate the products described in this special issue. The research and application usages of the MODLAND products, and more generally of any remote sensing products generated in a routine manner, put a high priority on providing statements concerning product performance. The correct interpretation of scientific information from global, long-term series of remote sensing products requires the ability to discriminate between product artifacts and changes in the Earth processes being monitored. Product performance information is required by users in order to consider products in their appropriate scientific context, and is required by the algorithm developers to identify products that are performing poorly so that improvements may be implemented.

The MODLAND ST has coordinated and developed protocols to evaluate the performance of the MODLAND products through quality assessment (QA) and validation activities. The objective of MODLAND QA is to evaluate and document the scientific quality of the MODLAND products with respect to their intended performance. MODLAND QA results are stored in the products at the pixel level and as metadata at the product file level. This enables users to consult QA results when ordering and using products to ensure that the products have been generated without error or artifacts. In many cases, MODLAND products can only be used meaningfully after consideration of this information. MODLAND validation quantifies product accuracy over a range of representative conditions (Morisette, Privette, & Justice, 2002, this issue). Validation is performed by analytical comparison of product samples

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with independently derived data that include field measurements and remote sensing products with established uncertainties (Justice et al., 2000). The results of validation are made available to the user community by publication in the scientific literature and on Web sites, typically within 2 years after the independent data sets are collected. Users should consider this information with respect to the accuracy requirements of their applications. Validation results are not intended to capture all artifacts and issues that may reduce the accuracy of individual product instances.

Product errors may be introduced by numerous, sometimes interrelated, causes that include: instrument errors; incomplete transmission of instrument and ephemeris data from the satellite to ground stations; incomplete instrument characterization and calibration knowledge; geolocation uncertainties; use of inaccurate ancillary data sets; software coding errors; software configuration failures (whereby interdependent products are made with mismatched data formats or scientific content); algorithm sensitivity to surface, atmospheric and remote sensing variations; and errors introduced by the production, archival and distribution processes. Although every attempt is made to ensure that the MODLAND products are generated without error, it is generally neither desirable nor practical to delay their distribution until products are proven error-free or until known errors have been removed by product reprocessing. This is because errors may be introduced at any time during the life of the instrument and may not be identified for a considerable period, because errors may be negated by appropriate user action or may have benign impacts for certain applications, and because the user community plays an important, although informal, role in performing product validation and quality assessment.

This paper describes the MODLAND product QA approach. The approach has been developed over the last 5 years and represents a new approach in assessing and ensuring the performance of land remote sensing products that are generated in a systematic manner. This paper presents an overview and procedural description of the QA approach with some limited examples selected from the first year of MODLAND production when the MODIS instrument calibration and the MODIS land products were still being refined.

2. MODLAND organization and products

The MODLAND ST is located at eight Science Computing Facilities (SCFs) distributed across the United States. The ST members at each SCF are responsible for developing the science algorithms and processing software used to produce one or more of the MODLAND products. Standard and intermediate MODLAND products are produced by the MODIS Adaptive Processing System (MODAPS) with a daily average production, at the time of writing, of more than 10,000 data files and a volume of more than 390 gigabytes. The products are global in coverage and will be produced for the designed 6-year lifetime of each MODIS instrument onboard NASA's Earth Observing System (EOS) Terra and Aqua satellites. The standard MODLAND products are sent to Distributed Active Archive Centers (DAACs) for archive and distribution to the user community (Justice et al., 1998). The MODLAND cryospheric products are sent to the National Snow and Ice Data Center DAAC and the non-cryospheric land products are sent to the Earth Resources Observation Systems Data Center DAAC. The DAAC archival and distribution components are facilitated by the EOS Data Information System (EOSDIS) and its infrastructure, the EOSDIS Core System (ECS) (Asrar & Ramapriyan, 1995). The SCF personnel may order samples of the MODLAND products that have been recently produced from the MODAPS, and order other MODIS and EOS products from the DAACs.

The role of the MODAPS is to process MODIS instrument data into a hierarchy of increasingly refined products. Fig. 1 illustrates the standard MODLAND products and their interdependencies. MODLAND products are derived from calibrated MODIS instrument data (Guenther et al., 1998), in conjunction with geolocation products (Wolfe et al., 2002, this issue), MODIS atmospheric products (e.g., cloud mask and aerosol products) (Ackerman et al., 1998; Kaufman et al., 1997), static ancillary data sets (e.g., land–sea mask), and the dynamic outputs of data assimilation and Earth system models (e.g., Data Assimilation Office water vapor product) (Schubert, Pfaendtner, & Rood, 1993). The products are generated in a hierarchy of processing levels: retrieved geophysical parameters at the same location as the MODIS instrument data (Level 2), earth-gridded geophysical parameters (Level 2G and Level 3), and earth-gridded model outputs (Level 4). The smallest unit of MODLAND data processed at any one time is defined at Level 2 as a granule, and at Levels 2G, 3 and 4 as a tile. A granule corresponds to 5 min of MODIS sensing and covers approximately 2340×2030 km in the across and along track directions, respectively. MODLAND Level 2 products sensed over a 12-h period 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. Level 2G products are temporally composited to make daily, 8-day, 16-day, and 32-day Level 3 and Level 4 products. The tiled products (Levels 2G–L4) are defined in a global non-overlapping grid in the equal area Integerized Sinusoidal projection (Rossow & Garder, 1984). Globally, there are 460 tiles, of which 326 contain land pixels. Each tile has fixed Earth-locations covering an area of approximately 1200×1200 km ($10° \times 10°$ at the equator). All MODLAND products are stored in an enhanced Hierarchical Data Format, known as HDF-EOS (WWW1). The HDF files are composed of multidimensional data arrays known as science data sets,

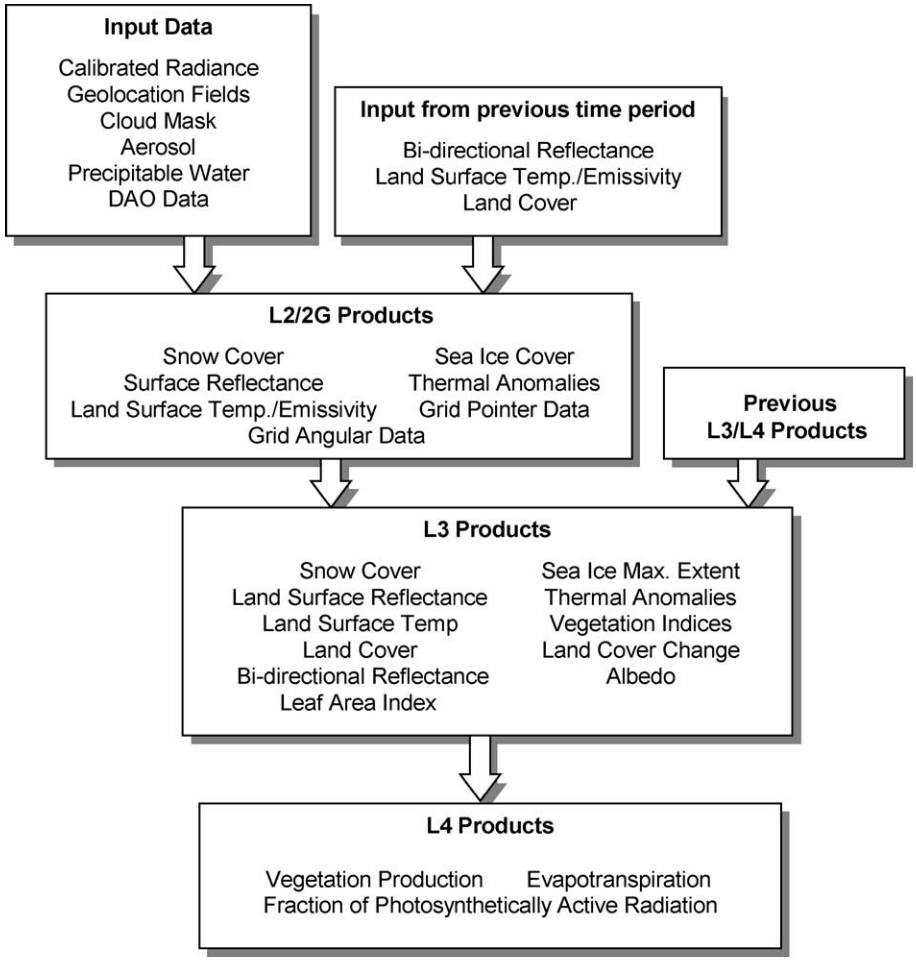


Fig. 1. MODIS land data processing overview.

and metadata. All products are assigned filenames that uniquely identify them by date and time of sensor acquisition and production.

3. MODLAND QA roles

The ST is responsible for providing quality assessment of the MODLAND products. This process is time-consuming, complex and difficult to manage because of the large number of products, the dependencies that exist between them, and because different QA procedures are applied to each product. The MODIS Land Data Operational Product Evaluation (LDOPE) facility was formed to support the MODLAND ST and to provide a coordination mechanism for MODLAND's QA activities. The LDOPE is staffed by a small group of scientific and technical staff and is located in close physical proximity to the MODAPS to enable efficient communication with the production managers and to ensure rapid data access. The LDOPE personnel undertake routine QA of all the MODLAND products, track the quality of non-MODLAND input products (e.g., the MODIS calibrated radiances and cloud mask products), check for error propagation through interdependent MODLAND products, develop and maintain QA tools and procedures, disseminate QA results and information within the ST, and ensure that the MODLAND QA results are available to the public.

The SCF personnel perform QA on the products for which they are responsible, and may also perform QA on the input data used to generate their products. The QA process is the first step in problem resolution. SCF personnel update production codes and/or science algorithms to rectify issues that have been identified in their products, and to handle issues found in the input products that their algorithms require. Experience with global product generation has shown that algorithms are subject to evolution with product refinement, often resulting in multiple product versions (Townshend, 1994). This has been the case with MODIS in the early post-launch era. For example, the MODIS land surface reflectance code was updated 14 times in the first year of MODIS data availability. The SCF personnel inform the LDOPE personnel of their QA findings and advise on algorithm/code updates and scientific findings that may influence product quality.

The MODAPS processing and DAAC archival staff are responsible for ensuring the non-scientific quality of the

Table 1
QA information stored for every pixel in all MODLAND products, summarized as four QA metadata indicating the percentage of pixels in the granule/tile with each QA code

Per pixel QA code	Meaning
00	Pixel produced, good quality, not necessary to examine more detailed QA
01	Pixel produced, unreliable or unquantifiable quality, recommend examination of more detailed QA
10	Pixel not produced due to cloud effects
11	Pixel not produced primarily due to reasons other than cloud

products. They seek to ensure that production codes are correctly configured, that products are made using the correct input data, and that the products are not corrupted in the production, transfer, archival, or retrieval processes. The DAAC staff includes personnel who provide technical and scientific support to the user community. User feedback provides an informal but important role in the QA process. Users are encouraged to contact DAAC User Services to provide feedback on the scientific quality of the MODLAND products (WWW2; WWW3). This information will be forwarded to the LDOPE and SCF personnel by DAAC User Services personnel as appropriate.

3.1. MODLAND QA documentation

The formal results of MODLAND QA are descriptive statements concerning product quality and are stored as metadata and as per-pixel QA information within each product. These results are generated in the production code and by post-production assessment. The format and mechanisms for the retrieval of MODLAND QA results have been designed to accommodate diverse users including the ST, production managers, and the user community.

MODLAND per-pixel QA results are generated by the production code for specific science data sets in each granule/tile. Per-pixel QA data differ considerably between products and levels and are too numerous to describe in this paper (the interested reader is referred to the MODLAND product User Guides found by following links at WWW4). Products that can have meaningful error estimates assigned to them store per-pixel uncertainty estimates and/or ranges: for example, the land surface temperature product stores emissivity and temperature error estimates. Information on external factors known to affect product quality and consistency is also stored for each product. These data include atmospheric conditions (e.g., cloud cover); surface type (e.g., ocean, coast, wetland, inland water); scan, solar and viewing geometry; and whether dynamic ancillary data or backup estimates have been used as input (e.g., aerosol climatology estimates used to replace missing observations in the MODIS aerosol product). The science code processing history (such as the logical criteria used by the algorithm), the results of different algorithm tests, and whether the input data were useful, may also be stored. To aid users, and to enable consistent interpretation across all the MODLAND products, two generic QA bits are stored for each pixel, and are summarized over each granule/tile by four QA metadata (Table 1).

The MODLAND products include product-specific metadata in addition to metadata that describe temporal and geographic attributes, version information, filenames of the input data used to generate the product, and granule/tile level summaries of per-pixel QA information. All EOS products carry metadata summarizing the results of QA procedures performed by the production code and performed by the ST after the products are generated (Lutz et al., 2000). These are shown in Table 2. The Automatic Quality metadata are set by the production code to document granules/tiles that meet certain criteria, for example, to indicate granules/tiles that should be investigated or that have failed a certain test at a specified level. These metadata may be used by the processing system to mediate production (e.g., a granule is not used to produce a downstream product if the granule has an Automatic Quality Flag set to "Failed"). It is not possible or practical to write software that handles every source of error that may occur. Consequently, the ST must periodically assess samples of the products. The results of these assessments are documented in the Science Quality metadata.

The Science Quality metadata carry the most detailed quality information so that users can make informed choices when ordering products. The Science Quality Flag is set to one of seven valid states (Table 2) and the associated Science Quality Flag Explanation describes the setting and provides supporting information. The ST and LDOPE staff may update the Science Quality metadata at any time to reflect their QA analyses. The metadata may be updated for all the instances of a product or with increasing specificity: for example, with respect to certain geographic and temporal domains, to a particular algorithm version, or to individual product granules and tiles. By default, all MODLAND products are initially set with a Science Quality Flag of "Not Investigated" and with a blank Science Quality Flag Explanation (WWW5).

Table 2
Summary QA metadata common to all MODLAND products

QA metadata name	Valids	Set
Automatic Quality Flag	Passed, Failed, Suspect	during production by science software
Automatic Quality Flag Explanation	Explanatory text (255 characters)	
Science Quality Flag	Passed, Failed, Suspect, Inferred Passed, Inferred Failed, Being Investigated, Not Investigated (default)	after production by the Science Team
Science Quality Flag Explanation	Explanatory text (255 characters)	

3.2. The utility of MODLAND QA results

The ST examine per-pixel and QA metadata generated during production in order to check algorithm code function, to make inferences useful for future algorithm development, and to identify granules/tiles that should be selected for more detailed QA. The MODLAND production managers inspect the Science Quality metadata and respond to LDOPE and SCF reports on product quality and algorithm updates in order to develop product processing and distribution plans. If the products have sufficiently severe errors (e.g., all pixel values are incorrectly set to zero) then their distribution to the DAACs and/or their continued production in the MODAPS may be halted pending problem resolution.

Users are encouraged to inspect the Science Quality metadata when they order products to decide on product utility in the context of their applications. Products that have been labeled with failed Science QA should not be ordered, or should be used with caution. When products are obtained, users may examine the per-pixel QA information and product-specific QA metadata to filter data that are unsuitable for their applications and to develop error budgets and appropriate processing criteria in their procedures and analyses. The per-pixel QA information stored in the MODLAND products should be examined. In many cases, MODLAND products can only be used meaningfully after careful consideration of this information.

3.3. MODLAND QA information flows

The LDOPE personnel maintain a number of Web sites and a QA database to facilitate the MODLAND QA process. Internet technology is used to support remote access by the geographically distributed ST. After QA has been performed, any identified product issues are posted on a MODLAND Known Product Issues Web site with examples, algorithm version and occurrence information (WWW6). Product issues are categorized as "pending," "closed," "reopened," or "note," and are updated by the LDOPE personnel to reflect the current production status. The Known Product Issues Web site has proven to be an effective way to record the propagation of issues through the dependent hierarchy of MODLAND products and to passively communicate information within the ST. Fig. 2 illustrates an issue posted on the Known Product Issues Web site. In the early post-launch stage, the MODIS cloud product (Ackerman et al., 1998) was found to falsely flag certain bright sparsely vegetated areas as cloud. This had important ramifications for many of the MODLAND products. The known issue illustrated in Fig. 2 describes how the 16-day Nadir Bidirectional Reflectance Distribution Function (BRDF) Adjusted Reflectance (NBAR) product (Schaaf et al., 2002 this issue) was systematically not generated over sparsely vegetated land in the Sahel because of this "upstream" product problem. The highlighted blue text link

Case #:DR_MOD43_01012 **Opening date:** 01/12/01 **Last update:** 01/12/01
Status: Note

MOD43 is not produced when there are insufficient observations to invert the BRDF model. The cloud mask has been found to systematically label some desert transition regions as cloudy even when they are clear. MOD43 production is precluded in these regions. For example, the transition zone between grass savanna and desert shrubland across North Africa is seen to be all fill values in the mosiac image below.

MOD43B4. A2000305.h16v07.001.2001010133426.hdf
MOD43B4. A2000305.h17v07.001.2001010135420.hdf
MOD43B4. A2000305.h18v07.001.2001010135906.hdf
MOD43B4. A2000305.h19v07.001.2001010140948.hdf
SDS: Nadir_Reflectance
(True-color composite with fill values in white)

Occurence: From day 2000295 onward (also some granules from days 284, 286, 287 and 290)
PGE:2.2.9

Fig. 2. Example Known Product Issue posted at (WWW6). See text for more details.

in Fig. 2 points to a separate, more detailed description of the cloud mask problem posted elsewhere on the site. This cloud mask issue was subsequently rectified by a change to the cloud mask algorithm, and the status of the posting changed from "Note" to "Closed."

The information posted on the Known Product Issues Web site enables the LDOPE and SCF personnel to check the progress of issue resolution and thereby ensure correct product quality documentation in the Science Quality metadata. The Science Quality metadata are stored in an LDOPE QA database (described later), which is populated with the metadata of every MODLAND product and may be queried by the ST. Recently updated Science Quality metadata are sent from the LDOPE QA database to the relevant DAACs so that they are available to the public as part of the DAAC data order process. At the time of writing, the Science Quality metadata are not being populated in the EOSDIS Core System and so the EOS Data Gateway (used to order products from the DAACs) should not be used to query against these metadata. Until this problem is rectified, the Science Quality metadata are provided on a MODLAND QA Web site (WWW5). The user community is advised to examine this Web site when ordering MODLAND products.

3.4. QA sampling

It is not possible for the ST and LDOPE to assess every MODLAND product granule and tile because of the high data volume. The proportion of MODLAND production that can be assessed directly is constrained by finite data processing, computer network and disk storage capacities and also by the availability of qualified personnel at the SCFs and LDOPE. Dedicated MODLAND network resources have been allocated to accommodate a throughput of approximately 10% of the average daily production volume. In practice, limited human resources and the time involved in performing QA reduces the number of product granules and tiles that may be examined. Consequently, a number of sampling strategies and tools have been developed to enable representative product samples to be selected for QA purposes, and to enable synoptic quality assessment of a large number of MODLAND granules/tiles.

Synoptic product assessments are performed by the LDOPE and SCF personnel by visual inspection of coarse spatial resolution global browse products and by examination of product metadata through querying the LDOPE QA database. The LDOPE personnel also maintain and monitor a time series of summary statistics derived from all Level 2G, 3, and 4 MODLAND products at a number of globally distributed locations. Where inspections of the global browse, LDOPE QA database metadata, and/or time series information indicate low product quality or anomalous behavior, the relevant product granules/tiles are ordered for more detailed assessment. The global browse data, LDOPE QA database, and time series analyses are described in more detail below. In addition to these synoptic sampling approaches, product samples are selected in a purposeful manner where algorithm understanding can predict expected problems, to check the impact of code updates and known issues through the hierarchy of MODLAND products, and in order to confirm or negate suspected problems due to exogenous factors. Systematic and gross product issues, such as those introduced by coding errors, inaccurate static ancillary data sets, or noisy instrument detectors, require only limited investigation to establish their causes. Until these types of errors are rectified or handled by the production code, they are observed in products in a predictable and repetitive manner and have their Science Quality metadata set accordingly. Issues that are suspected of being related to algorithm sensitivity to surface variations (e.g., land cover or relief variations), atmospheric variations (e.g., aerosol content, sub-pixel cloud), or remote sensing variations (e.g., sun-surface-sensor geometry) are more complex to diagnose and must be confirmed or negated by examination of representative product samples.

3.4.1. Global browse

The ST has developed coarse spatial resolution versions of the MODLAND products to enable synoptic product evaluation with reduced data volume. The coarse spatial resolution products are generated with an approximate resolution of 5 km using aggregation schemes that are appropriate for the specific product. For example, the coarse resolution fire product labels fire pixels as those where fire was detected in any of the 25 corresponding full-resolution 1 km pixels. Continuous data products, such as land surface reflectance, are generally aggregated by computing mean values. The coarse spatial resolution products contain aggregated per-pixel QA information and subsets of the parent product metadata. They are generated by the MODAPS and are made available to the ST.

In order to provide rapid synoptic product assessment via the Internet, selected coarse spatial resolution product science data sets are projected into a global coordinate system and displayed on a MODLAND QA Web site (WWW7). These global browse images are generated in the JPEG format with fixed contrast stretching and color look-up tables to enable consistent temporal comparison. They are represented at two scales with pixel sizes corresponding to 20 and 40 km in the Hammer–Aitoff projection (Snyder, 1987). The polar sea ice global browse images are defined with pixel sizes of approximately 14.5 and 28.3 km in the Lambert Azimuthal Equal Area projection (Snyder, 1987). The global browse Web page is updated every 6 h with the coarse spatial resolution products made during that period. The Web page interface has been developed to support interactive selection of products, rapid browsing through the product time series, and zooming and panning at 5 km resolution. Fig. 3 illustrates a combined Level 2 active fire and land surface reflectance global browse for Julian Day 281, 2000. The MODIS sensing geometry and the cloud cover are clearly evident. In addition to providing a synoptic

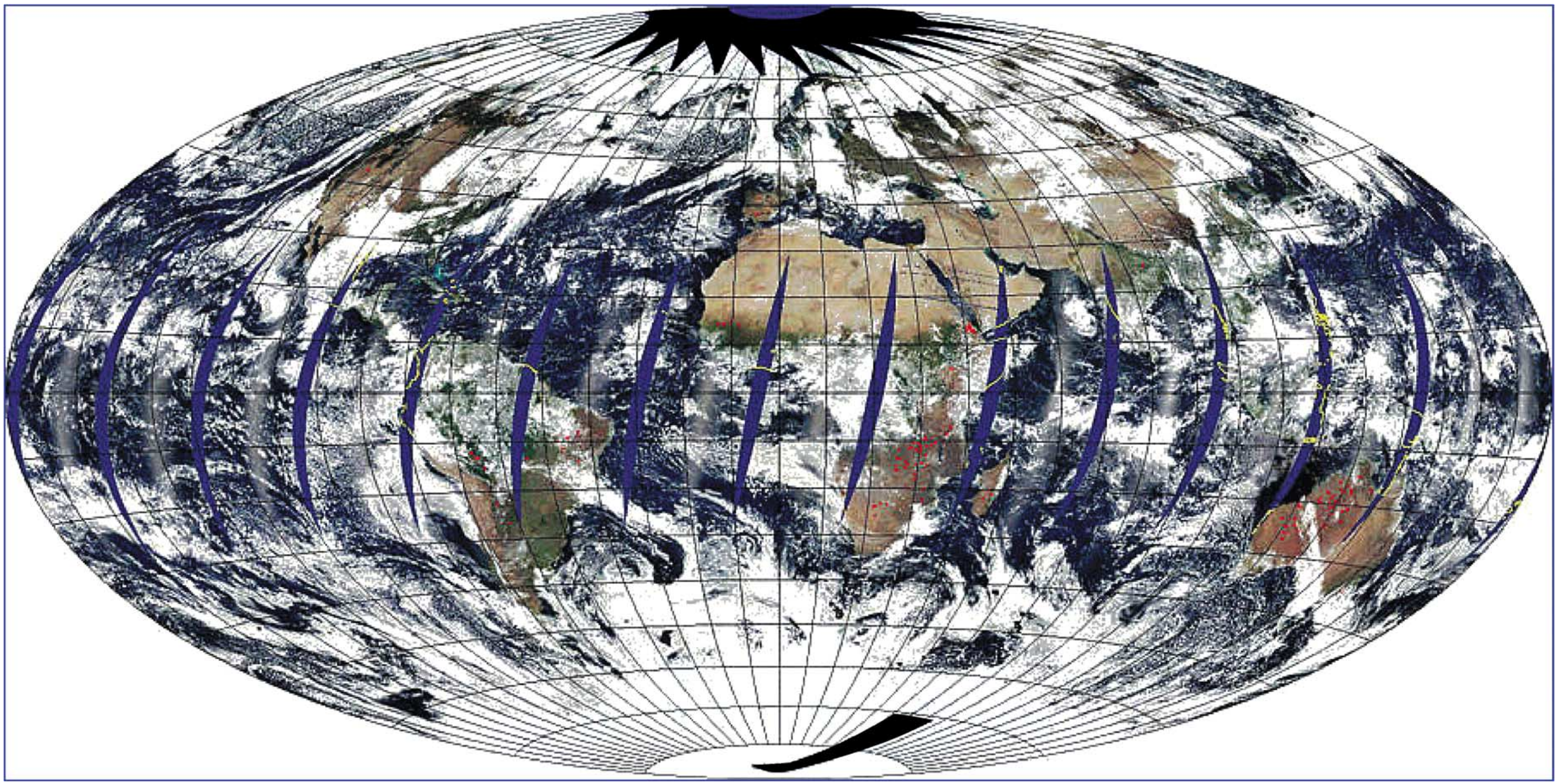
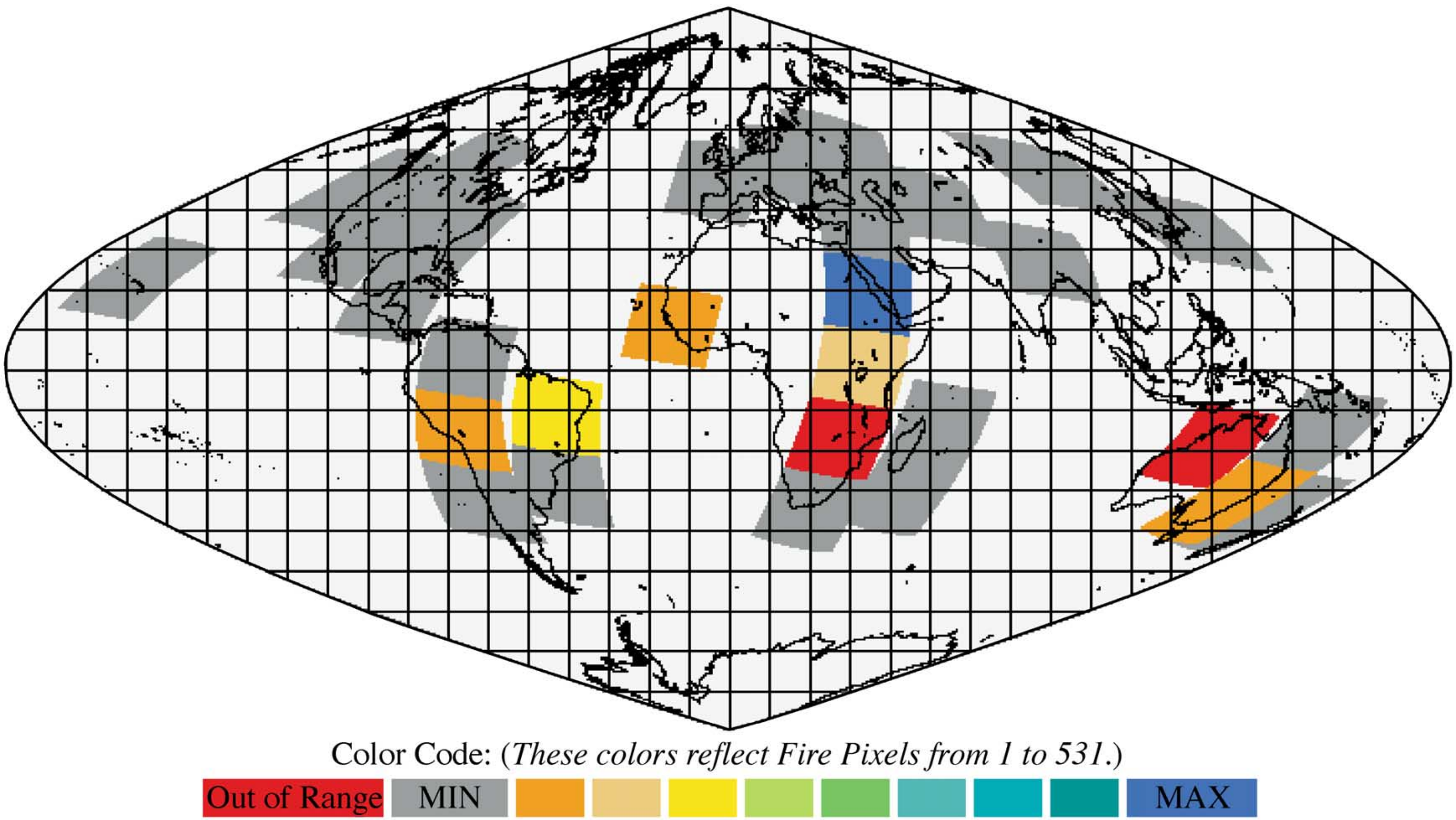


Fig. 3. Twenty-kilometer global browse image sensed on Julian Day 281, 2000 showing MODIS land surface reflectance overlain with locations of MODIS active fire detections. The MODIS 0.645, 0.555, and 0.469 μm land surface reflectances are displayed as red, green and blue, respectively. The red dots illustrate the 1 km locations of MODIS active fires detected on this day.



There are 30 records found.

Search Criteria:
ESDT=MOD14
Acquisition Date: from 2000281 to 2000281
Day/Night Flag = Day
AND Fire Pixels > 0
Display only lastest processing granules.

Fig. 4. Results of LDOPE QA database query for the daytime 1 km Level 2 fire product granules sensed on Julian Day 281, 2000 which have “Fire Pixel” metadata values (i.e., number of detected active fires) greater than zero. The granules are shaded with a contrast stretch reflecting “Fire Pixel” metadata values in the range 1–531. The granules that are shaded red have “Fire Pixel” metadata values greater than 531.

global view of the cloud cover and the production status, the global browse images allow gross product problems to be detected. Currently, the global browses do not enable assessment of all science data sets in each MODLAND product or assessment of the product metadata.

3.4.2. LDOPE QA database

The LDOPE QA database was developed to meet ST requirements for flexible examination of product metadata via the Internet. The database is populated with the metadata of every MODLAND product as the products are generated by MODAPS. By querying the LDOPE QA database against temporal, spatial, and metadata attributes of interest, the ST may infer which products have low quality. Given this information, the ST user may decide whether or not to obtain these products for QA purposes and whether to query the database for additional information in order to investigate the likely causes of detected or suspected problems. A number of database query types are supported including Boolean and relational operators against all product metadata values, querying using a global map, and querying against the production date/time and the sensor acquisition date/time. Query results may be displayed as text lists, metadata bar graphs, metadata scatter plots, or as global maps shaded with metadata values. All query result displays are interactive, allowing the ST user to "point and click" in order to examine the metadata of the selected granule or tile. The hierarchy of MODLAND products may be navigated via the metadata that store the filenames of the input data sets used to generate each product. Metadata queries may be used to identify the conditions under which known quality issues occur. The Science Quality metadata of individual products, or products selected as the result of complex queries, may be updated by SCF and LDOPE users who have appropriate privilege levels. These metadata information are periodically sent to the DAACs for use by the terrestrial science community.

Fig. 4 illustrates the results of an LDOPE QA database query for daytime Level 2 fire product granules (Justice et al., 2002, this issue) sensed on Julian Day 281, 2000 that had "Fire Pixel" metadata values greater than zero. The "Fire Pixel" metadata store the number of active fires detected within each granule. The granules are shaded with a contrast stretch reflecting "Fire Pixel" metadata values in the range 1–531, and the red shaded granules have "Fire Pixel" metadata values greater than 531. Any of the metadata in the 30 granules returned by this query, and any range of metadata values, could have been selected for display in this manner. In this example, "Fire Pixel" metadata are selected to display a global view of detected

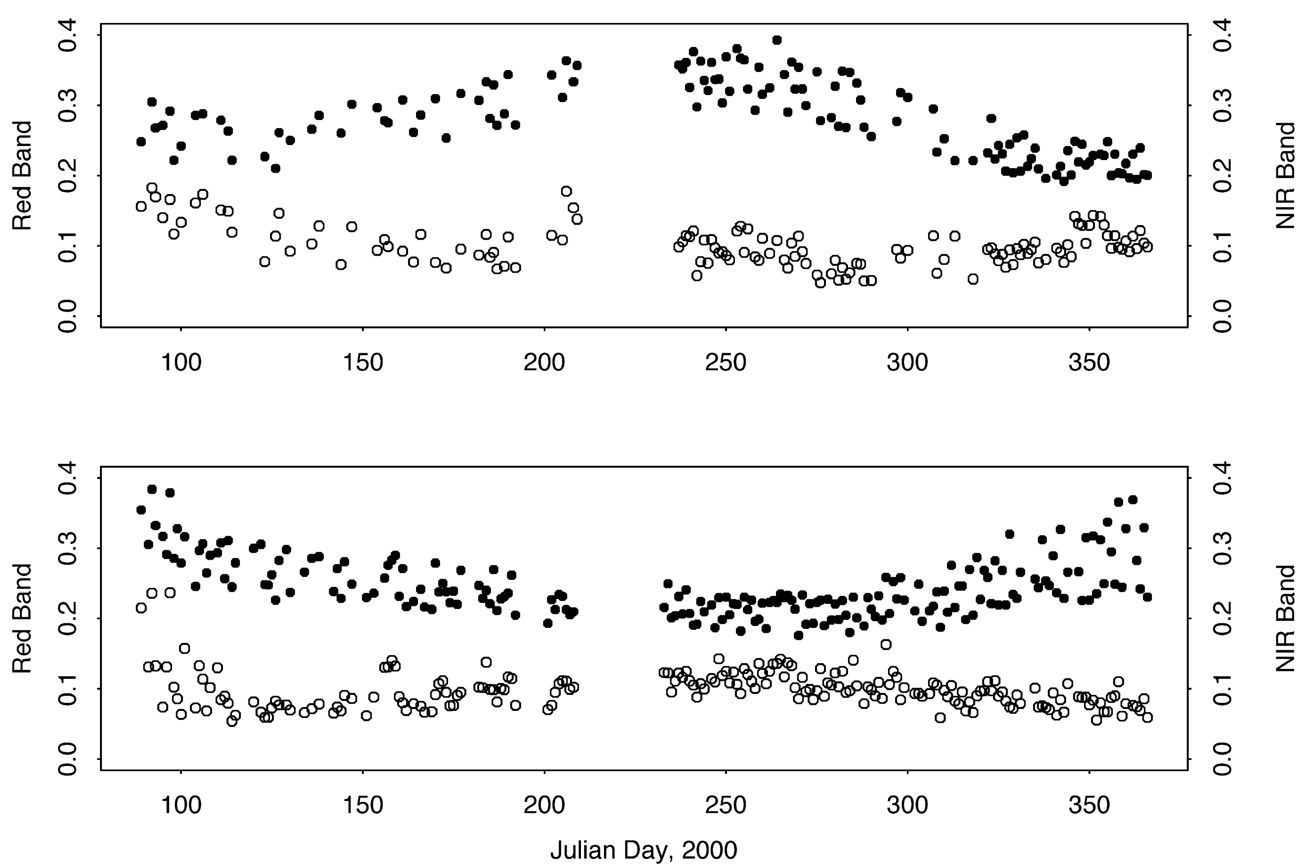


Fig. 5. Time series of mean red (0.645 μm) [open circles] and near-infrared (0.858 μm) [closed circles] daily 500 m L2G land surface reflectance extracted from the savanna biome for tiles in Northwestern Africa centered at 5.3°W, 15.0°N (top) and Southern Africa centered at 27.9°E, 25.0° S (bottom). The mean daily statistics were computed from approximately 250,000 and 550,000 pixels in the Northwestern and Southern Africa tiles, respectively.

active fires. The global browse example (Fig. 3) is for the same day as the query result, and the active fires detected over Australia, Africa and South America are evident in both figures.

3.4.3. Time series analysis

A time series of summary statistics derived from all the gridded MODLAND products at a number of fixed globally distributed locations is maintained and monitored by LDOPE personnel in order to identify anomalous product behavior. At certain SCFs, the ST members also perform time series analyses at product-specific sites. Product time series analyses are important because they capture algorithm sensitivity to surface (e.g., vegetation phenology), atmospheric (e.g., aerosol loading) and remote sensing (e.g., sun-surface-sensor geometry) conditions that change temporally, and because they allow changes in the instrument characteristics and calibration to be examined (Guenther et al., 1998; Los, 1998). In many cases, issues that affect product performance are seen only through examination of long-term product series or by examination of temporally composited products. As of this writing, approximately 1 year of MODIS data has been processed. Consequently, seasonality and events that occur on time scales shorter than 1 year are apparent, in addition to variations due to exogenous product issues. As with any change detection, the temporal and spatial scale of analysis will impact the ability to extract diagnostic information. Initial results indicate that temporal product intercomparisons and consideration of different spatial and temporal scales of the MODLAND products allow both problem identification and for simple inferences to be developed to explain their causes.

Time series analyses are performed on a limited number of geographically fixed locations because of resource constraints. The analyses are performed on a number of land tiles over areas which best represent the variability of the majority of the MODLAND products. Shortly after Terra launch, well-characterized MODIS data were not available. Therefore, tile selection was based on the MODIS at-launch land cover product as the majority of the MODLAND products are sensitive to or are explicitly concerned with land cover. The tiles were selected to represent numerous

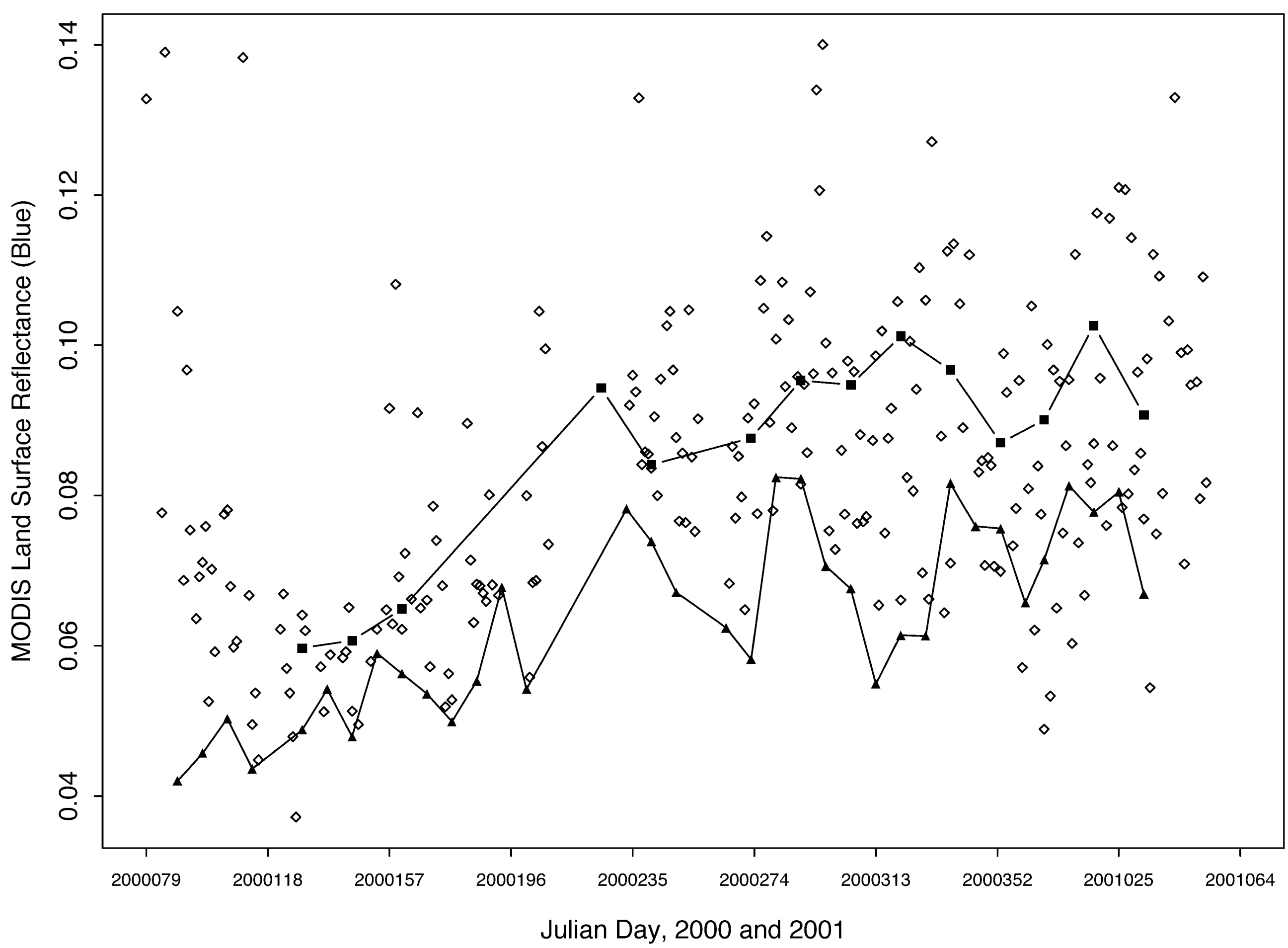


Fig. 6. Time series of mean blue (0.469 μm) daily 500 m L2G [open diamonds], 500 m 8-day land surface reflectance [closed triangles], and 16-day nadir BRDF-adjusted (NBAR) 1 km reflectance [closed squares] extracted from the shrubland biome in the Southern Africa tile (centered at 27.9°E, 25.0° S). The closed symbols denote the start of the 8-day and 16-day periods. Approximately 194,000, 269,000 and 53,000 pixels were used to calculate each daily L2G, 8-day and 16-day mean value, respectively.

cover types permitting meaningful analyses of as many MODLAND products as possible in each tile. Summary statistics of high-quality, cloud-free science data set pixel values are calculated for each product by masking products with their per-pixel QA information. Mean, standard deviation, minimum and maximum statistics are calculated in each tile over 3×3 km sites, on a land cover class basis, and on a biome basis. The 13 land cover classes in the MODIS at-launch land cover product (Hansen, Defries, Townshend, & Sohlberg, 2000) were remapped to a set of seven biomes described by Myneni, Nemani, and Running (1997), while the 3×3 km sites were selected interactively within each land cover class. The site and tile selection have not noticeably affected the time series analysis results presented here. Clearly the statistics could be summarized over any categorical spatial database. A quantitative tile and site selection procedure will be implemented after the MODIS land cover product (Friedl et al., 2002, this issue) has been produced from a full year of MODIS data. The following examples illustrate the prototype time series analyses.

Fig. 5 shows time series plots of the mean red (0.645 μm) and NIR (0.858 μm) daily Level 2G land surface reflectance (Vermote, El Saleous, & Justice, 2002, this issue) sensed in 2000 over two tiles in northwestern and southern Africa. The mean reflectance values are computed over the savanna biome type, and exhibit a high-frequency temporal variability associated with the bidirectional reflectance properties of most natural surfaces (Schaaf et al., 2002, this issue) and residual atmospheric contamination by cloud and aerosols. The plots immediately convey two important points with respect to QA. In terms of product availability, there are obvious data losses over the time series, most notably from Julian days 193–199 and from Julian days 218–232. During the first of these periods, there was a production problem retrieving data from the instrument data archive, and during the second period, no useful calibrated MODIS instrument data were available due to a problem with the MODIS onboard data formatter. Secondly, the opposing phenological signals in the Northern and Southern hemispheres indicate that the product is performing, on a gross level, as expected. In the southern Africa tile, the red and NIR data reach maximum and minimum seasonal values, respectively, during the southern Africa dry season around Julian days 230–270, while contemporaneously, in the northwestern Africa tile, the red and NIR reflectance reach their minimum and maximum seasonal values, respectively.

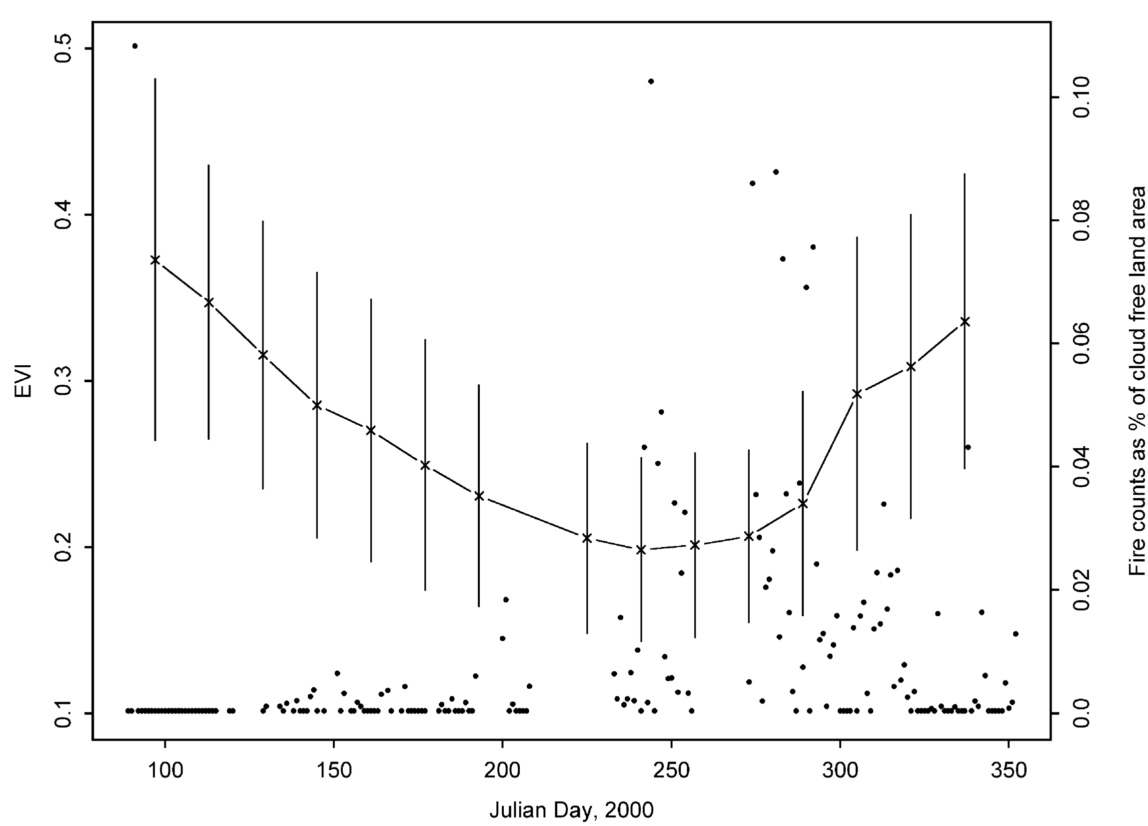


Fig. 7. Time series of mean 16-day 1 km Enhanced Vegetation Index (EVI) and daily 1 km fire counts [closed circles] extracted over the savanna biome in the Southern Africa tile (centered at 27.9°E, 25.0° S). Fire counts are expressed as a percentage of the cloud-free savanna biome land area. EVI variability is plotted as a vertical line through each data point, representing one standard deviation about the mean. Approximately 240,000 and 250,000 pixels were used to compute the EVI and fire count data for each plotted point, respectively.

Time series analysis can also reveal the effects of algorithm changes. Fig. 6 shows mean blue (0.469 μm) land surface reflectance data for the shrubland biome type derived from daily L2G and 8-day composited products (Vermote et al., 2002, this issue) and the 16-day nadir BRDF-adjusted reflectance (NBAR) product (Schaaf et al., 2002, this issue). Land surface reflectance data are sensitive to aerosol contamination at this wavelength and show high daily variability. The 8-day product, which is based on a minimum blue compositing criterion through Julian Day 336, is smoother than the L2G daily product, and generally tracks the minimum values of the daily data over each 8-day period. As a result of routine QA (in this case, visual inspection was sufficient), the compositing algorithm was found to preferentially select shadow data and was augmented with a shadow test and minimum view zenith angle constraint after day 336. The effect of this compositing algorithm change on the blue channel statistics can be seen after day 336, when the 8-day data no longer track the daily minimum. The 16-day NBAR product, which incorporates a correction to nadir viewing geometry and the median solar zenith angle for the time period, is smoother again as bidirectional reflectance effects are minimized. The missing 16-day NBAR product time series values are due to early production problems and low availability of cloud-free observations.

Intercomparison of different product time series provides a powerful QA approach when underpinned by an understanding of how the products should be related. Fig. 7 shows the mean and standard deviation of the 16-day 1 km Enhanced Vegetation Index (EVI) product (Huete et al., 2002, this issue) computed within the savanna biome in the southern Africa tile. The number of active fires detected daily (Justice et al., 2002, this issue), expressed as a percentage of the cloud-free savanna biome area, is superimposed for comparative purposes. The frequency of burning closely follows the seasonal pattern of senescence following the end of annual rains, and the illustrated distributions are similar to those found with AVHRR time series (e.g., Kendall, Justice, Dowty, Elvidge, & Goldammer, 1997). The very high active fire count on the first day, which seems out of place with respect to the EVI temporal signal, was due to an algorithm coding error. As indicated by the standard deviation about the mean EVI, the within-biome EVI variability is reduced in the dry season. This may be because vegetation heterogeneity is reduced under

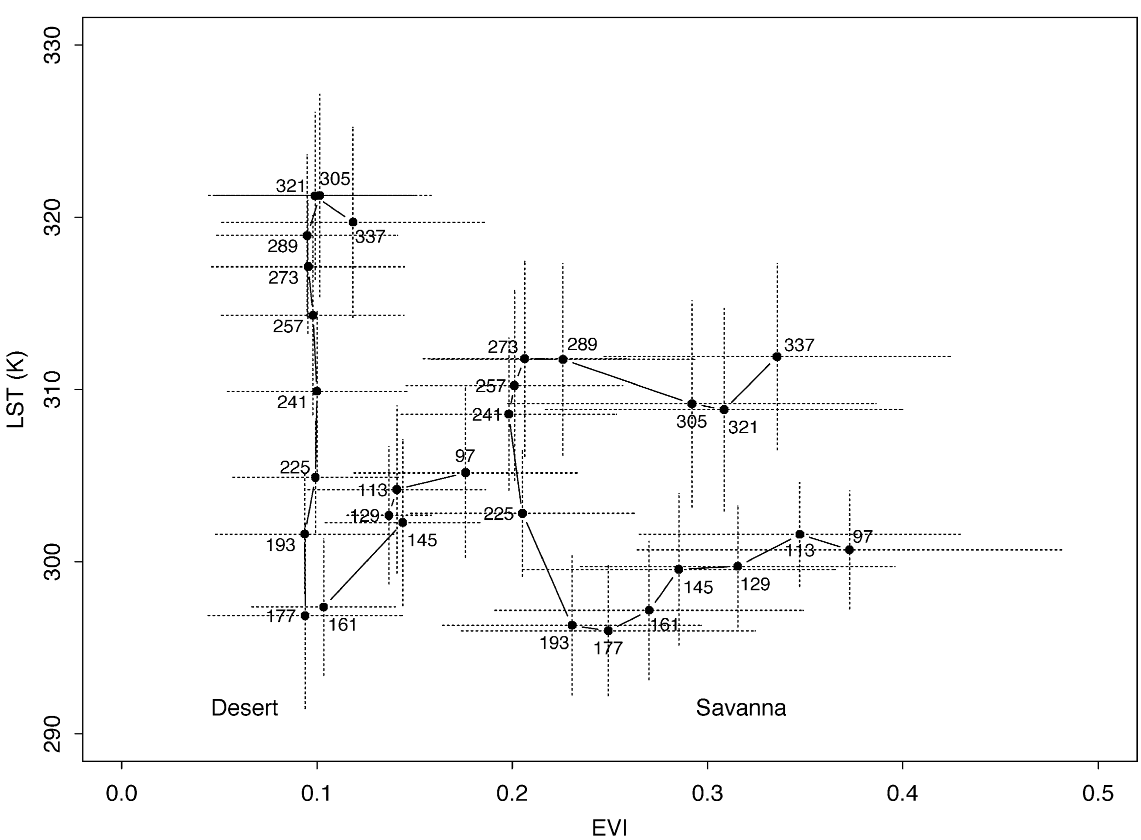


Fig. 8. Time series of mean 16-day 1 km land surface temperature against mean 16-day 1 km EVI extracted from the desert and savanna biomes in the Southern Africa tile (centered at 27.9°E, 25.0° S). The numbers illustrate the Julian Day at the beginning of each 16-day period. The standard deviations of these data are plotted as dotted lines about the mean values. For each plotted point, approximately 6000 and 300,000 pixels were used to compute the desert and savanna temperature values, respectively, and approximately 3000 and 240,000 pixels were used to compute the desert and savanna EVI values, respectively.

dry conditions. Note that the standard deviations are large and suggest that examination over smaller areas is required for more sensitive product quality assessment.

The time series statistics are computed at different spatial scales (e.g., with respect to tile biomes and with respect to 3 × 3 km sites) in order to capture different types of product issues and to provide a trade-off between increased probability of capturing issues over spatially extensive biomes against enhanced detection sensitivity at the site level. This is illustrated in Figs. 8 and 9, which show plots of 16-day maximum-value land surface temperature (LST), composited from the daily 1 km LST product (Wan, Zhang, Zhang, & Li, 2002, this issue), versus EVI for savanna and desert land cover types in the southern Africa tile. Figs. 8 and 9 show these data extracted at the biome and 3 × 3 km site level, respectively. The savanna biome plot follows a counterclockwise curve as EVI and surface temperature track their expected seasonal trajectories (Lambin & Ehrlich, 1996). The desert biome statistics, however, show some seasonality in EVI, particularly in the early days of the time series, which suggests that this class is a mixture of both vegetated and non-vegetated areas. A MODIS tile typically includes multiple examples of a single biome under significantly different surface conditions, and other factors, such as atmospheric state, can change very rapidly across short distances. Fig. 9 shows the LST and EVI statistics computed over 3 × 3 km sites located in the desert and savanna biomes. As expected, the within-site variability is much lower than the within-biome variability depicted in Fig. 8. The desert site exhibits virtually no seasonality in EVI, indicating the presence of little if any vegetation at this location, with all of the temporal variability limited to the LST. At the savanna site, the temporal trajectory is less smooth than the biome-level plot, with an apparent reversal in the trajectory occurring on Julian Day 193. The standard deviation about the mean EVI for this data point is much greater than for any other date in the time series which may be related to site-level surface variability. A product quality issue is more likely, however. Examination of the EVI product metadata for day 193 revealed that only 9 days of input data were used to generate the 16-day product. This data loss was due to production system problems retrieving data from the MODIS instrument data archive. The reduction in the number of observations reduces the likelihood of atmospherically clear, near-nadir pixels being available, reducing the expected product quality. This effect is not seen in the corresponding biome plot, however, illustrating the utility of this multiscale analysis.

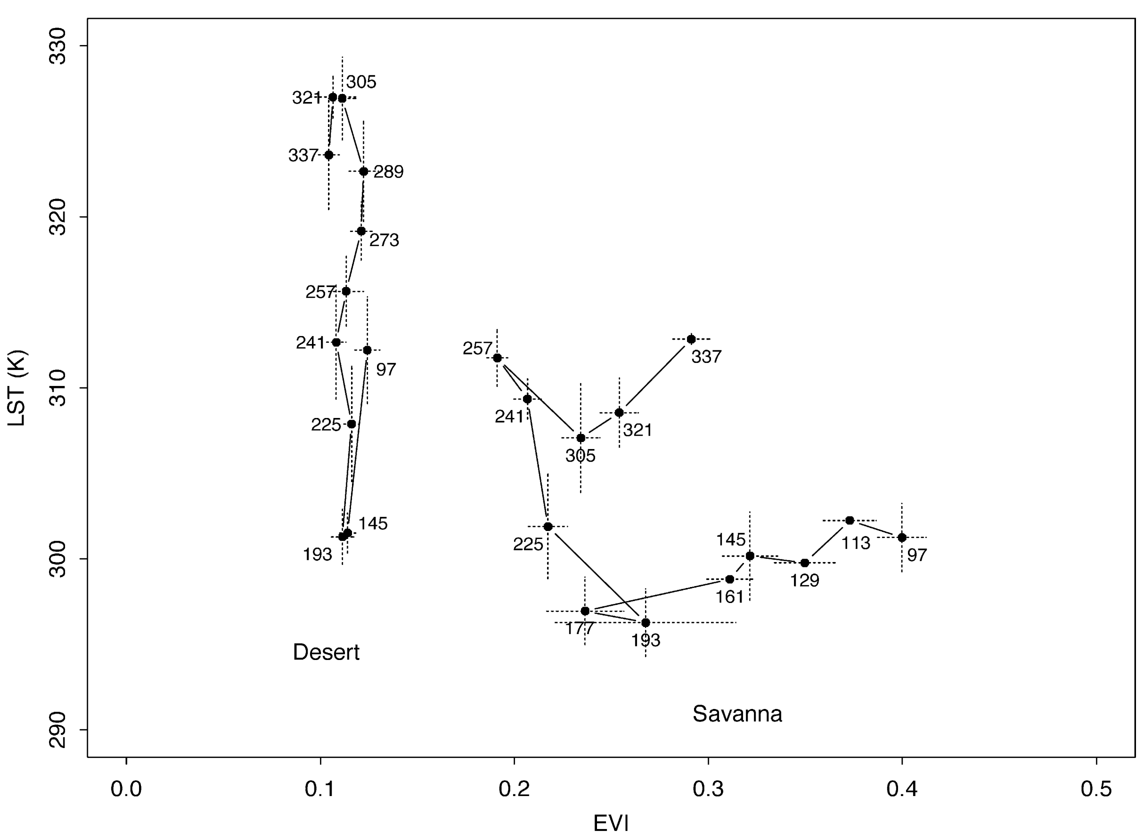


Fig. 9. Time series of mean 16-day 1 km land surface temperature against mean 16-day 1 km EVI extracted over desert and savanna 3 × 3 km sites located at 22.38°E, 25.28°S and 31.21°E, 23.51°S, respectively. The numbers illustrate the Julian Day at the beginning of each 16-day period. The standard deviations of these data are plotted as dotted lines about the mean values. For each plotted point, an average of 9.0 pixels were used to compute the desert and savanna temperature values, and an average of 6.8 and 8.5 pixels were used to compute the desert and savanna EVI values, respectively.

4. Conclusion

The product quality assessment approach described in this paper provides an indication of the importance that is being given to product quality by the MODIS Land Science Team. The results of MODLAND QA are stored as metadata and as per-pixel QA information and should be examined by users when they order and use the MODLAND products. The MODLAND QA approach is an integral link in the MODLAND production chain and is a formal step in the process of rectifying product issues through algorithm updates and product reprocessing. Some MODLAND products are without heritage, and QA procedures and indicators of product quality are expected to evolve as the Science Team and the user community learn more about the product characteristics.

The first year of MODLAND production has required a steep learning curve. In this period, the MODIS Land Science Team updated the production code an average of five times per product as a result of QA. Understanding the behavior of multiple interrelated products has been challenging, particularly within a systematic production context and given the large MODLAND production volume. After the first year of MODLAND products has been processed, interannual product comparisons will commence with the goal of automating aspects of the LDOPE QA process. Automated QA procedures will be investigated to support the potential 10-fold increase in data volume anticipated as a result of simultaneous product reprocessing and production of MODLAND products from the Terra and Aqua data streams. The QA approach described in this paper provides an approach for assessing and documenting the quality of future remote sensing data sets.

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References

Ackerman, S. A., Strabala, K. I., Menzel, W. P., Frey, R. A., Moeller, C. C., & Gumley, L. E. (1998). Discriminating clear sky from clouds with MODIS. *Journal of Geophysical Research*, *103*, 32141–32157.

Asrar, G., & Ramapriyan, H. K. (1995). Data and information system for mission to planet earth. *Remote Sensing Reviews*, *13*, 1–25.

Friedl, M.A., McIver, D.K., Hodges, J.C.F., Zhang, X.Y., Muchoney, D., Strahler, A.H., Woodcock, C.E., Gopal, S., Schnieder, A., Cooper, A., Bacinni, A., Gao, F., & Schaaf, C. (2002). Global land cover mapping from MODIS: algorithms and early results. *Remote Sensing of Environment*, *83*, 288–303 (this issue).

Guenther, B., Godden, G. D., Xiong, X., Knight, E. J., Qiu, S.-Y., Montgomery, H., Hopkins, M. M., Khayat, M. G., & Hao, Z. (1998). Prelaunch algorithm and data format for the Level 1 calibration products for the EOS-AM1 Moderate Resolution Imaging Spectroradiometer (MODIS). *IEEE Transactions on Geoscience and Remote Sensing*, *36*, 1142–1151.

Hansen, M. C., Defries, R. S., Townshend, J. R. G., & Sohlberg, R. (2000). Global land cover classification at 1 km spatial resolution using a classification tree approach. *International Journal of Remote Sensing*, *21*, 1331–1364.

Huete, A. R., Didan, K., Miura, T., Rodriguez, E. P., Gao, X., & Ferreira, L. G. (2002). Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sensing of Environment, 83,* 195–213 (this issue).

Justice, C. O., Belward, A., Morisette, J., Lewis, P., Privette, J., & Baret, F. (2000). Developments in the 'validation' of satellite sensor products for the study of the land surface. *International Journal of Remote Sensing*, *21*, 3383–3390.

Justice, C. O., Giglio, L., Korontzi, S., Owens, J., Alleaume, S., Morisette, J. T., Roy, D. P., Petitcolin, F., Descloitres, J., & Kaufman, Y. J. (2002). Global fire products from MODIS. *Remote Sensing of Environment, 83,* 245–263 (this issue).

Justice, C. O., Vermote, E., Townshend, J., Defries, R., Roy, D., Hall, D., Salomonson, V., Privette, J., Riggs, G., Strahler, A., Lucht, W., Myneni, R., Knyazikhin, Y., Running, S., Nemani, R., Wan, Z., Huete, A., van Leeuwen, W., Wolfe, R., Giglio, L., Muller, J.-P., Lewis, P., & Barnsley, M. (1998). The Moderate Resolution Imaging Spectroradiometer (MODIS): land remote sensing for global change research. *IEEE Transactions on Geoscience and Remote Sensing*, *36*, 1228–1249.

Kaufman, Y. J., Herring, D. D., Ranson, K. J., & Collatz, G. J. (1998). Earth observing system AM1 mission to earth. *IEEE Transactions on Geoscience and Remote Sensing*, *36*, 1045–1055.

Kaufman, Y. J., Tanre, D., Remer, L. A., Vermote, E. F., Chu, A., & Holben, B. N. (1997). Operational remote sensing of tropospheric aerosol over land from EOS moderate resolution imaging spectroradiometer. *Journal of Geophysical Research-Atmospheres*, *102*(D14), 17051–17067.

Kendall, J. D., Justice, C. O., Dowty, P. R., Elvidge, C. D., & Goldammer, J. G. (1997). Remote sensing of fires in Southern Africa during the SAFARI 1992 campaign. In B. Van Wilgen, M. Andreae, J. Lindesay, & J. A. Lindesay (Eds.), *Fire in Southern African Savannas* (pp. 89–133). Johannesburg, South Africa: Witwatersrand Univ. Press.

Lambin, E. F., & Ehrlich, D. (1996). The surface temperature–vegetation index space for land cover and land-cover change analysis. *International Journal of Remote Sensing*, *17*, 463–487.

Los, S. O. (1998). Estimation of the ratio of sensor degradation between NOAA AVHRR channels 1 and 2 from monthly NDVI composites. *IEEE Transactions on Geoscience and Remote Sensing*, *36*, 206–213.

Lutz, B., Roy, D., Leff, C., Lewicki, S., Geir, E., Ziskin, D., Kilpatrick, K., Chu, A. (2000). A review of EOS Terra quality assessment (QA). *Proceedings of IEEE Geoscience and Remote Sensing Symposium 2000 (IGARSS), Honolulu, HI, 24–28 July.* (CD-ROM INT_27_06.pdf, 0-7803-6362-0/00 (c) 2000 IEEE).

Morisette, J., Privette, J., & Justice, C. O. (2002). A framework for the validation of MODIS Land products. *Remote Sensing of Environment, 83,* 77–96 (this issue).

Myneni, R., Nemani, R., & Running, S. W. (1997). Estimation of global leaf area index and absorbed PAR using radiative transfer models. *IEEE Transactions on Geoscience and Remote Sensing*, *35*, 1380–1393.

Rossow, W. B., & Garder, L. (1984). Selection of a map grid for data-analysis and archival. *Journal of Climate and Applied Meteorology, 23* (8), 1253–1257.

Schaaf, C. B., Gao, F., Strahler, A. H., Lucht, W., Li, X., Tsang, T., Strugnell, N., Zhang, X., Jin, Y., Muller, J. -P., Lewis, P., Barnsley, M., Hobson, P., Disney, M., Roberts, G., Dunderdale, M., Doll, C., d'Entremont, R. P., Hu, B., Liang, S., Privette, J., & Roy, D. (2002). First operational BRDF, Albedo and Nadir reflectance products from MODIS. *Remote Sensing of Environment, 83,* 135–148 (this issue).

Schubert, S. D., Pfaendtner, J., & Rood, R. (1993). An assimilated data set for Earth science applications. *Bulletin of the American Meteorological Society*, *74*, 2331–2342.

Snyder, J. P. (1987). Map projections—a working manual. *US Geological Survey Professional Paper, vol. 1395*. Washington, DC: US Government Printing Office.

Townshend, J. R. G. (1994). Global data sets for land applications from the Advanced Very High-Resolution Radiometer—an introduction. *International Journal of Remote Sensing*, *15*, 3319–3332.

Vermote, E. F., El Saleous, N. Z., & Justice, C. O. (2002). Atmospheric correction of MODIS data in the visible to middle infrared: first results. *Remote Sensing of Environment, 83,* 97–111 (this issue).

Wan, Z., Zhang, Y., Zhang, Q., & Li, Z.-L. (2002). Validation of the land-surface temperature products retrieved from Terra Moderate Resolution Imaging Spectroradiometer data. *Remote Sensing of Environment, 83,* 163–180 (this issue).

Wolfe, R. E., Nishihama, M., Fleig, A., Kuyper, J., Roy, D. P., Storey, J., & Patt, F. (2002). Achieving sub-pixel geolocation accuracy in support of MODIS Land science. *Remote Sensing of Environment, 83,* 31–49 (this issue).

Wolfe, R. E., Roy, D. P., & Vermote, E. F. (1998). The MODIS land data storage, gridding and compositing methodology: L2 grid. *IEEE Transactions on Geoscience and Remote Sensing*, *36*, 1324–1338.

WWW1, The National Center for Supercomputing Applications HDF Web site, http://hdf.ncsa.uiuc.edu/.

WWW2, EROS Data Center DAAC User Services Web site, http://edcdaac.usgs.gov/contact.html.

WWW3, National Snow and Ice Data Center DAAC User Services Web site, http://nsidc.org/forms/contact.html.

WWW4, MODIS Land Discipline Web site—Land Product Families, http://modis-land.gsfc.nasa.gov/products/.

WWW5, MODIS Land QA Web site—Product Quality Documentation, http://landdb1.nascom.nasa.gov/QA_WWW/release.cgi.

WWW6, MODIS Land QA Web site—Known Product Issues, http://landdb1.nascom.nasa.gov/QA_WWW/issues.html.

WWW7, MODIS Land Global Browse Images, http://modland.nascom.nasa.gov/browse/.