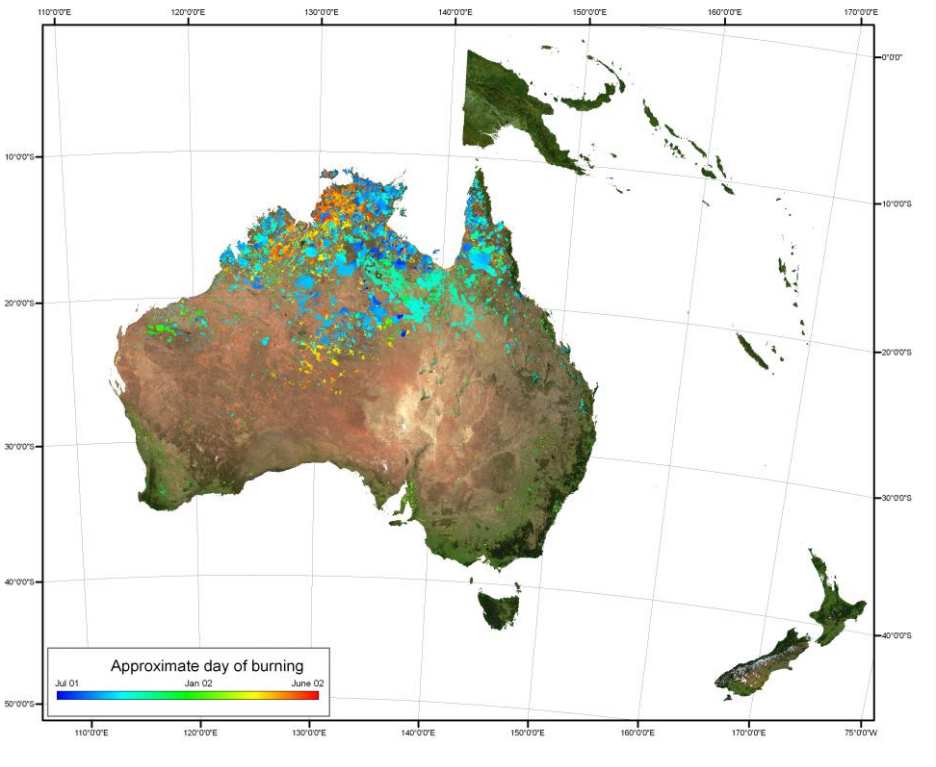
MODIS Collection 5.1 Burned Area Product - MCD45



User's Guide

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ABBREVIATIONS AND ACRONYMS

BA	Burned Area
BRDF	Bidirectional Reflectance Distribution Function
CMG	Climate Model Grid
EOS	(NASA) Earth Observing System
EOSDIS	EOS Data Information System
Geotiff	Georeferenced Tagged Image File Format
HDF	Hierarchical Data Format
LP-DAAC	Land Processes Distributed Active Archive Center
MCD45	MODIS global burned area product
MODIS	Moderate Resolution Imaging Spectrometer
NDVI	Normalized Difference Vegetation Index
SDS	Science Data Set
Sz	Sun Zenith Angle
QA	Quality Assessment
Vz	View Zenith Angle

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1 Introduction

Mapping the timing and the extent of fires is important as fire is a prominent change agent affecting ecosystem structure and the cycling of carbon and nutrients as well as is a globally-significant cause of greenhouse gas emission. Satellite data have been used to monitor biomass burning at regional and global scale for more than two decades using algorithms that detect the location of active fires at the time of satellite overpass and in the last decade using burned area algorithms that map directly the spatial extent of the area affected by fires. Previously and in the absence of accurate burned area products, burned area assessments have been created based on calibrating the available active fire data from regional AVHRR and global MODIS data. However several remote sensing, environmental, and fire behavior factors limit the accuracy of such derived fire affected area data sets.

The availability of robustly calibrated, atmospherically corrected, cloud-screened, geolocated data provided by the latest generation of moderate resolution remote sensing systems allows for major advances in satellite mapping of fire affected area. A complementary MODIS algorithm defined to map fire affected area has been developed and the first global burned area product from 2000 onwards is now being generated as part of the MODIS Land collection 5.1 product suite.

This document provides practical information about the MODIS Burned Area Product (MCD45), including product and algorithm description, ordering and download procedures, data layer descriptions, and known problems. The guide also provides a few examples on how to perform basic operations with the product using some widely used software packages.

2 Terminology of the MODIS Burned Area Product

This section explains some of the standard technical terms used in the documentation of the standard MODIS products.

2.1 Processing Levels (from the EOS data products handbook):

- Level 0 - Reconstructed unprocessed instrument/payload data at full resolution; any and all communications artifacts (e.g., synchronization frames, communications headers) removed.
- Level 1A - Reconstructed unprocessed instrument data at full resolution, time-referenced, and annotated with ancillary information, including radiometric and

geometric calibration coefficients and georeferencing parameters (e.g., platform ephemeris) computed and appended, but not applied, to the Level 0 data.

- Level 1B - Level 1A data that have been processed to sensor units (not all instruments have a Level 1B equivalent).
- Level 2 - Derived geophysical variables at the same resolution and location as the Level 1 source data.
- Level 3 - Variables mapped on uniform space-time grid scales, usually with some completeness and consistency.
- Level 4 - Model output or results from analyses of lower level data (e.g., variables derived from multiple measurements).

2.2 Tiles

MODIS Level 2 and higher products are defined on a global 250 m, 500 m, or 1 km sinusoidal grid where spatial resolution is defined by the individual products (Level 0 and 1 are granule-based, a simple unprojected segment of the MODIS orbital swath). Grids are divided into fixed-area tiles of approximately 10 degrees x 10 degrees in size. Each tile is assigned a horizontal (h) and vertical (v) coordinate ranging from 0 to 35 and 0 to 17 respectively (Figure 1). The tile in the upper left corner is designated as h0,v0. A detailed description of the sinusoidal projection, and all the formulas needed for transformations between tile and geographic coordinates is provided in Appendix II.

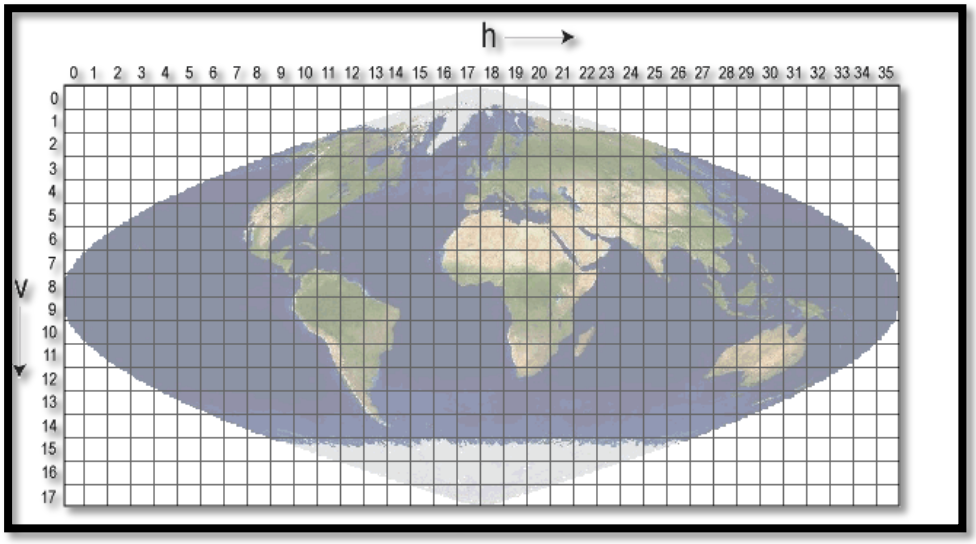

Figure 1: MODIS tiling scheme

2.3 Collections

Reprocessing of the entire MODIS data archive is performed periodically so as to incorporate better calibration, algorithm refinements, and improved upstream products into all MODIS products. The updated MODIS data archive resulting from each reprocessing is referred to as a collection. Later collections supersede all earlier collections.
The MCD45 MODIS Burned Area Product was not produced in Collections 1 through 4. It was produced for the first time as part of Collection 5, and it is available for the whole MODIS record (2000 to present).

2.4 MCD45 Nomenclature

All MODIS products are identified by an alphanumeric code of three letters and two numbers. The three letters define the data source, while the two numbers identity uniquely the product. The burned area product is named MCD45: MCD indicates that both MODIS Aqua and Terra data are used as input, and 45 is the identifier of the burned area product.

3 MCD45 Product Suite

Three different versions of the MODIS burned area product are available:

1. The official MCD45A1 in HDF-EOS format, which is available as part of the MODIS suite of global land products.
2. The re-projected monthly Geotiff version available from the University of Maryland.
3. The re-projected monthly Shapefile version available from the University of Maryland.

3.1 Level 3 Monthly Tiled Product: MCD45A1

The MCD45A1 Burned Area Product is a monthly Level 3 gridded 500 m product containing per-pixel burning and quality information, and tile-level metadata. Product users are provided with a variety of quality assessment information and a single summary quality assessment score for each pixel. A detailed description of the product is provided in section 4.
All the standard MODIS products adopt a nomenclature that provides information about the spatial and temporal coverage of the product, as well as about the version of the product. An example filename of the product is:

- MCD45A1.A2000306.h16v07.051.2006360205845.hdf

which can be read as:

a) MCD45A1 = MODIS level 3 Monthly tiled burned area product

b) A2000306 = year and Julian date of the starting day of the month covered by the product: 306 is the Julian date of Nov 1, hence 2000306 means that the product covers November 2000.

c) h16v07 = spatial extent: the file covers tile h16v07

d) 051 = version identifier. 051 indicates Collection 5.1

e) 2006360205845= processing day and time (year 2006, Julian day 360, 20h58'45")

This naming convention ensures that files always have a unique name: if a tile is reprocessed the last number, indicating the day and time in which the file was processed, will be different, thus avoiding any confusion with obsolete data.

The **Julian day** is defined as a dating system that divides the year into 12 months and 365 days (leap year 366 days) and a table can be found for example here:

- regular years: http://www.quadax.com/Support/Julian2009.pdf
- leap years: http://www.quadax.com/Support/Julian2008.pdf

3.2 Geotiff subset for GIS visualization and analysis: MCD45monthly

A user-friendly Geotiff version of the MCD45 product is derived from the standard MCD45A1 hdf version by University of Maryland. The Geotiffs are reprojected in Plate-Carrée projection and cover a set of sub-continental windows (Figure 2). A table containing the regions covered and bounding coordinates of the 24 windows (plus one sub-window) is available in Appendix III.

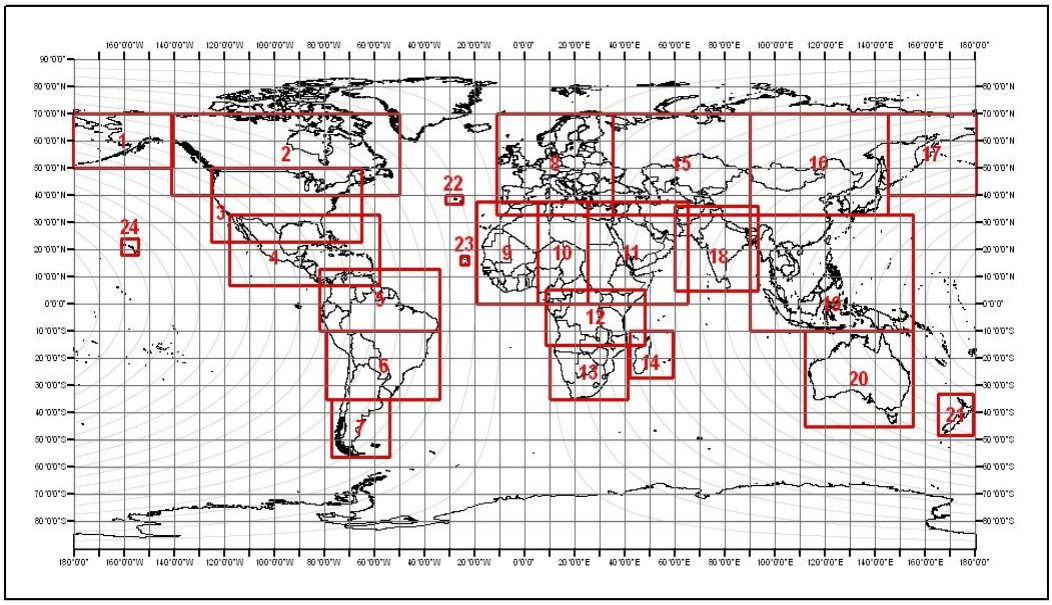

Figure 2: Coverage of the Geotiff subsets.

A high resolution version of the map, as well as a table with the bounding coordinates, is available in appendix III.

The Geotiffs follow a naming convention similar to the official MCD45A1 product. However, as the Geotiffs are obtained by mosaicing, resampling and reprojecting several tiles of the original product, the processing time is not available.

An example of filename of the product is:

- MCD45monthly.A2000306.Win01.051.burndate.tif
- MCD45monthly.A2000306.Win01.051.ba_qa.tif

which can be read as:

a) MCD45monthly = monthly Geotiff version of MCD45A1

b) A2000306 = year and Julian date of the starting day of the month covered by the product: 306 is the Julian date of Nov 1, hence 2000306 means that the product covers November 2000.

c) Win01 = spatial extent: the file covers window 1 (Alaska)

d) 051 = version identifier. 051 indicates Collection5.1

e) burndate/ba_qa = content of the file: unlike hdf, Geotiff files contain a single layer. At the moment, two layers of the original product are available as Geotiffs: "burndate" and "QA". See 3.4.3 for details.

3.3 Shapefile subset for GIS visualization and analysis: MCD45monthly

A shapefile version of the MCD45 product is derived from the monthly Geotiff version by the University of Maryland. The shapefiles are available with the same projection (Plate-Carrée) and geographic extent as the Geotiff sub-continental windows (Figure 2).

The shapefile naming convention is identical to the Geotiff naming convention. Each shapefile consists of multiple files which must remain in the same location relative to one another. An example of a shapefile, as available from the University of Maryland FTP, includes the following:

- MCD45monthly.A2000306.Win01.051.burndate.shp
- MCD45monthly.A2000306.Win01.051.burndate.shx
- MCD45monthly.A2000306.Win01.051.burndate.prj
- MCD45monthly.A2000306.Win01.051.burndate.dbf

which can be read as:

a) MCD45monthly = monthly shapefile version of MCD45A1
b) A2000306 = year and Julian date of the starting day of the month covered by the product: 306 is the Julian date of Nov 1, hence 2000306 means that the product covers November 2000.
c) Win01 = spatial extent: the file covers window 1 (Alaska)
d) 051 = version identifier. 051 indicates Collection5.1
e) burndate = content of the file. Only the "burndate" layer is available in the shapefile format. See 3.4.4 for details.

3.4 Contents of the MODIS Burned Area Product

The following text describes the content of the files; some of the layers of the product require knowledge of how the algorithm used for the production works; the detailed description of the algorithm can be found in Appendix I.

3.4.1 MCD45A1 Science Data Sets (SDS)

The product is distributed in the standard MODIS land format (HDF), and includes the following ten data Science Data Sets (i.e. layers), defining for each 500m pixel:

1. **Burn date** (2 bytes): Approximate Julian day of burning from eight days before the beginning of the month to eight days after the end of the month, or a code indicating unburned areas, snow, water, or lack of data.
    - 0 - unburned
    - 1-366 - approximate Julian day of burning
    - 900 – snow or high aerosol
    - 9998 - water bodies (internal)
    - 9999 - water bodies (seas and oceans)
    - 10000 - not enough data to perform inversion throughout the period
2. **BA pixel QA** (1 byte): Confidence of the detection (1 (most confident) to 4 (least confident)).
    - 1 - most confidently detected pixels, regardless of direction in time (forward, backward or both), passing test (4) described in appendix 1.
    - 2 - pixels where backward and forward direction in time predict the same change, passing test (5) described in appendix I.
    - 3 - pixels selected in the first stage of the contextual analysis.
    - 4 - pixels selected in the second stage of the contextual analysis.
    - 5 - detections over agricultural areas, according to the MCD12 land cover mask. Users are advised not to use those detections in any quantitative analysis, due to the low accuracy of burned area detection when fire is due to agricultural practices.
3. **Number of Passes** (1 byte): Number of observations where the temporal consistency test is passed.
4. **Number Used** (1 byte): Number of observations used in the temporal consistency test.
5. **Direction** (1 byte): Direction in time in which burning was detected (forward, backward or both).
    - 1 - forward
    - 2 - backward
    - 3 - both
6. **Surface Type (1 byte):** Information describing the land cover type and properties. The information is stored in the individual bits of the layer.
    - bit 0 (1=yes, 0=no): - water (NDVI < 0.1 and b7 < 0.04)
    - bit 1 (1=yes, 0=no) - low NDVI (NDVI < 0.1)

- bit 2 (1=yes, 0=no) - shallow, ephemeral, deep inland water (QA from MOD09 = 3, 4, 5 AND NDVI <0.1)
- bit 3 (1=yes, 0=no) - cloud (from MOD09 internal cloud mask)
- bit 4 (1=yes, 0=no) - cloud shadow (from MOD09 internal cloud mask)
- bit 5 (1=yes, 0=no) - view and solar zenith angle mask (Vz > 65 threshold or Sz > 65)
- bit 6 (1=yes, 0=no) - high view and solar zenith angle (Vz > 50 and Sz > 55)
- bit 7(1=yes, 0=no) - snow OR [high aerosol (from MOD09 QA) AND high view / solar zenith (Vz > 55 and Sz > 55)]

Example: if the Surface Type value of a pixel is 18, the corresponding binary number is 01001000; as bits 1 and 4 are set to 1, it means low NDVI and cloud shadow detected.

7. **Gap Range 1 (2 bytes):** Information describing the largest number of consecutive missing/cloudy days (if any) in the time series and the start day of the missing/cloudy period.
   - bits 0-8 - Julian day of the start of the gap
   - bits 9-13 - number of missing days including the start day

   Example: if the pixel value is 3372, the corresponding binary number is 001101001011000. The first nine bits (001101001) represent the number 300, the four following bits (0110) represent the number 6. Hence a six day gap starting at Julian day 300.

8. **Gap Range 2** (2 bytes): Information describing the second largest number of consecutive missing/cloudy days (if any) in the time series and the start day of the missing period.
   - bits 0-8 - Julian day of the start of the gap
   - bits 9-13 - number of missing days including the start day

3.4.2 MCD45A1 Metadata

In addition to the mandatory metadata required by the EOS Data Information System (EOSDIS) Core System (ECS), a set of product specific, tile-level metadata are included to enable the burned area product to be archived and ordered via ECS DAAC ordering systems.

The metadata report for each tile includes:

- The percentage of land pixels detected as burned.
- The percentage of pixels not processed due to insufficient cloud-free data.
- The percentage of pixels in each of the "BA pixel QA" categories.
- The number of pixels detected in each direction in time (forward, backward or both).

3.4.3 Geotiffs

Only two SDSs (layers) are available in Geotiff format. As explained in 3.2, for each month two files are available, one for each SDS:

1. **Burn date** (2 bytes): Approximate Julian day of burning within the month, or a code indicating unburned areas, snow, water, or lack of data. **Unlike the HDF version of the product, the GEOTIFFS do not include any overlap between consecutive months. The temporal filtering is described in Roy et al., 2008**.
    - 0 - unburned
    - 1-366 - approximate Julian day of burning within the month
    - 900 – snow or high aerosol
    - 9998 - water bodies (internal)
    - 9999 - water bodies (seas and oceans)
    - 10000 - not enough data to perform inversion throughout the period
    - -32768 - pixel not covered by any MODIS tile
2. **BA pixel QA** (1 byte): Confidence of the detection (1 (most confident) to 4 (least confident)).
    - 1 - most confidently detected pixels, regardless of direction in time (forward, backward or both), passing test (4) described in Appendix 1.
    - 2 - pixels where backward and forward direction in time predict the same change, passing test (5) described in section 4.1
    - 3 - pixels selected in the first stage of the contextual analysis
    - 4 - pixels selected in the second stage of the contextual analysis

3.4.4 Shapefiles

Only the "Burn date" SDS is available in shapefile format. Burn date values are stored in the "burndate" field of the shapefile. Unlike the burn date value in the Geotiff version, the shapefile burn date values include **only** the approximate Julian day of burning within the month, with values ranging from 1-366. All other values are discarded in the shapefile version of the MCD45monthly product. **For the discrimination between unburned and unmapped areas, users are recommended to download the HDF or GEOTIFF version of the product**

3.5 Forthcoming planned formats

1. MCD45 Climate Model Grid (CMG) Aggregated Burned Area Product

This product is currently under development. Data format information will be included at the time of product release.

2. MCD45 Yearly Synthesis Burned Area Product

This product is currently under development. Data format information will be included at the time of product release.

4 Obtaining the products

All MODIS products are available free of charge. The MODIS Burned Area Product is available for ordering from the Land Processes Distributed Active Archive Center (LP-DAAC) using the EOS Data Gateway web interface located at:

- http://reverb.echo.nasa.gov

Additionally, an ftp server is maintained by the University of Maryland, mostly to provide support to the science users who need to download systematically large volumes of data.

4.1 Downloading the products via FTP

The MODIS burned area product is available for download via ftp from the website

- http://modis-fire.umd.edu/

We request users to fill in a user online form for statistical purposes and in order to obtain username and password for the server. The form is available under

- http://modis-fire.umd.edu/form.asp

You are asked to enter your name, affiliation and a short description of the intended use of the product. A username and password is sent to your given e-mail address. Once you have received your username and password you can start retrieving the data either in HDF or Geotiff format.

For downloading the data via FTP you can use your current web browser such as the FTP extension of Firefox or Internet Explorer. However we recommend using special FTP software for downloading large amounts of data. You can use freely available software such as FileZillaClient or SmartFTP, which has the advantage that you can schedule your download to start at a later time and if you download multiple sources, it will try to download different portions from them to speed up.

- http://filezilla-project.org/download.php
- http://www.smartftp.com/

Whichever program you will use for data download you will need to connect to the given ftp site that is:

- ftp://ba1.geog.umd.edu

4.2 Data structure on FTP server

The HDF, Geotiff, and shapefile data sets are available on the same FTP server. However, the subdirectory structure is different and is described in the following paragraphs.

4.2.1 HDF files

The file system on the ftp server is structured to organize the data hierarchically by year and by month. All the data from the same month is located in a directory identified by the year and month as:

- /Collection51/HDF/YYYY/DDD/

where:

- YYYY is the year
- DDD is the julian day of the beginning of the month

For example, the directory /Collection51/HDF/2001/182 contains all the Collection 5.1 tiles (named with the convention explained in 3.1) of the product for July 2001.

4.2.2 Geotiff files and Shapefiles

The file system on the ftp server is structured to organize the data hierarchically by window, and then by year. All the data for the same window from the same year is located (for Geotiff files and shapefiles, respectively) in a directory identified as:

- /Collection51/TIF/WinXX/YYYY/
- /Collection51/SHP/WinXX/YYYY/

where:

- XX is the number of the window (figure 2)
- YYYY is the year

For example, the directory /Collection51/TIF/Win01/2001 contains all of the Collection 5.1 Geotiff files for months of 2001 for window 01 (Alaska).

5 Loading and processing the product into ENVI 4.8

5.1 MCD45A1 (hdf)

HDF MODIS products are only partially supported in ENVI.

To open them, instead of the File -> Open Image File menu, it is necessary to select

File -> Open External Files -> Generic Formats -> HDF

Opened as generic HDF, the files lose any geographic information. To restore it, it is necessary to enter manually the projection parameters.

Alternatively, it is possible to download and install the MODIS conversion toolkit developed by EXELIS:

- http://www.exelisvis.com/language/en-US/UserCommunity/CodeLibrary.aspx

5.2 MCD45monthly (Geotiff)

The Geotiff files are fully compatible with ENVI. To open them, it is possible to go simply through the File -> Open Image File menu.

5.3 MCD45monthly (Shapefile)

Shapefiles are not directly supported in ENVI, rather they are converted to the ENVI Vector File (.evf) format, then displayed on the screen. To load a shapefile, select

Vector -> Open Vector File -> Change file formats to Shapefile or All -> Select Shapefile

When prompted to set "Import Vector Files Parameters", set the desired layer name and output file location and select "OK". Do not adjust the projection information, the default values correspond to the Plate-Carrée projection used by the Geotiff files.

Use the "Available Vectors List" (Vector -> Available Vectors List) to overlay the vector on an existing display or display it in its own window.

6 Loading, displaying and processing the product in ArcGIS

Handling EOS-hdf files is not straightforward in ArcGIS. For the users of the official EOS-HDF product, we recommend to perform any scientific analysis in other software packages (e.g. ENVI) and then export to ArcGIS in a different format such as Geotiff.

6.1 MCD45monthly (Geotiff)

The Geotiffs can directly be loaded into ArcGIS through

-> Add Layer

In order to display the burned areas only, under

> Layer Properties> Unique Values >Symbology

Set the color to "No Color" for the following Values:

- 0 - unburned
- 900 – snow or high aerosol
- 9998 - water bodies (internal)

- 9999 - water bodies (seas and oceans)
- 10000 - not enough data to perform inversion throughout the period
- -32,768 – no data

ArcGIS will display the burned area in Julian days of the given month in either individual colors or in the same color depending on your settings. Figure 3 shows an example of MCD45monthly.A2010213.Win20.005.burndate.tif

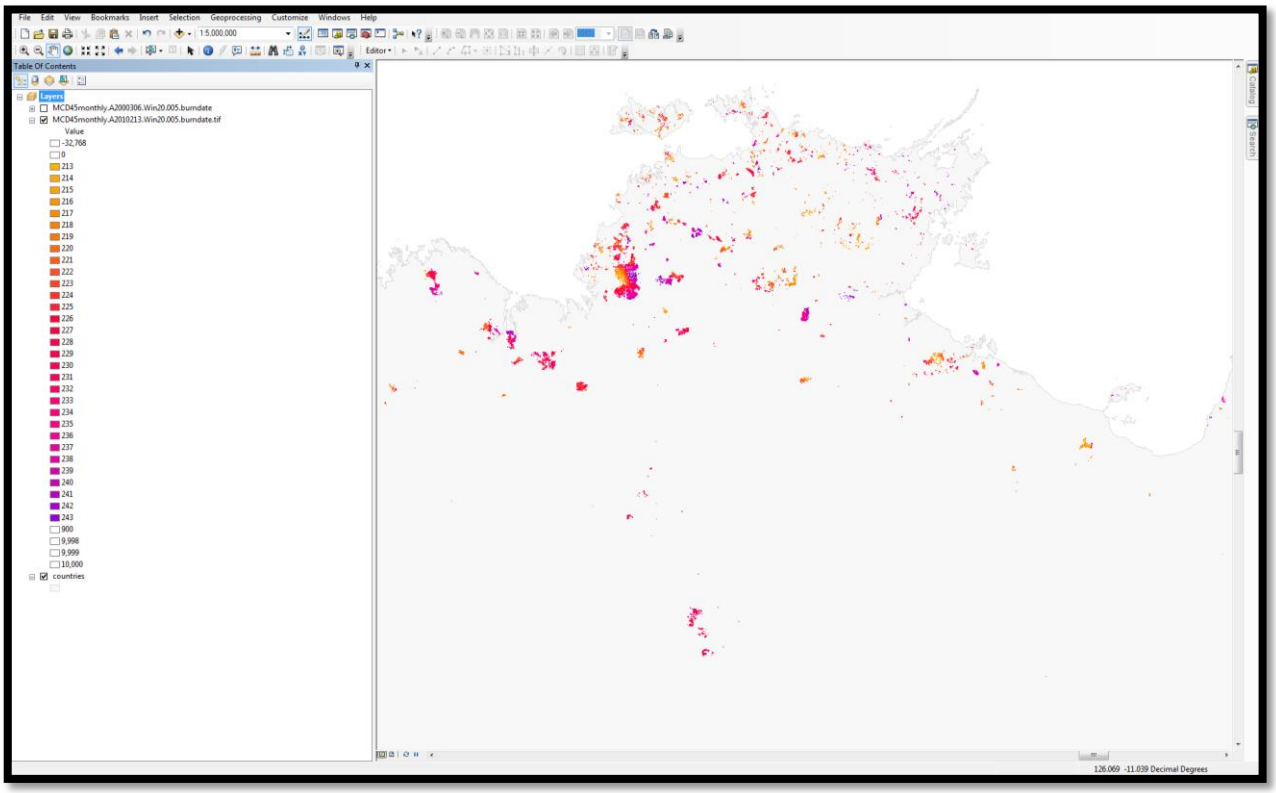

Figure 3: Display of Geotiff from August 2010, Window 20.

Each burn day of the month is shown in different colors

6.1.1 Area of Interest (AoI)

In order to reduce file size of the regional Geotiff and focus on a specific region an "Area of Interest (AoI)" can be subset.

->Display desired AoI

->Right mouse click data layer

->Data -> Export Data

The "Export Raster Data" window will open (figure 4). Check both data frames options to current and choose Format (TIFF).

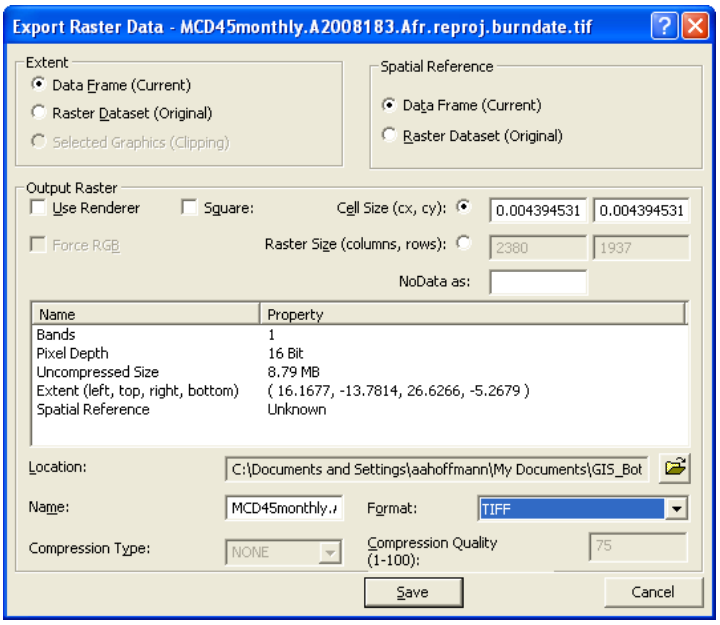

Figure 4: Export Raster data

6.2 MCD45montly (Shapefile)

The Shapefiles can directly be loaded into ArcGIS through

-> Add Layer

To change the appearance of the file, select

Layer Properties -> Symbology -> Graduated Colors

Optionally, to remove the outlines of the data, right click a symbol in the Graduated Colors panel and select "Properties For All Symbols", then set "Outline Color" to "No Color".

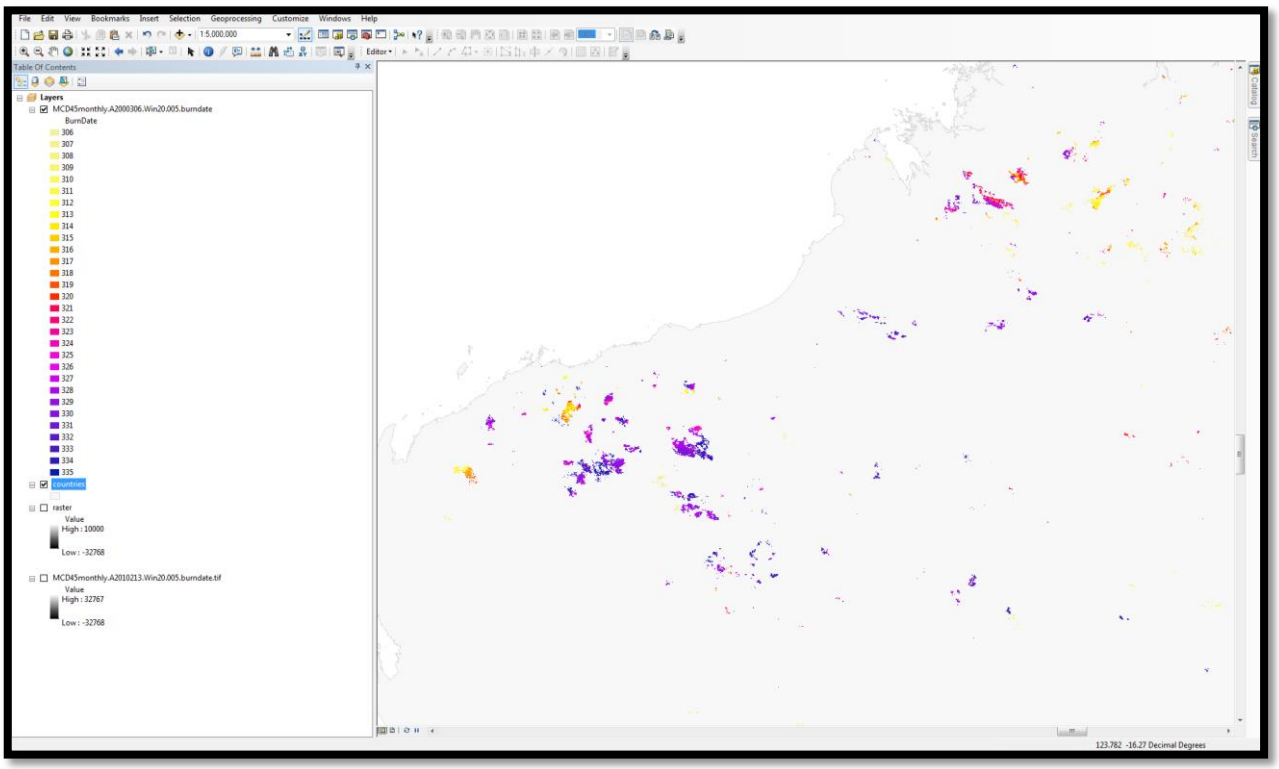

Figure 5: Display of Shapefile from November 2000, Window 20.

Each burn day of the month is shown in different colors

7 Caveats and Known Problems

The MODIS instrument had a prolonged outage in June 2001. As a consequence, not enough input data is available for the production of MCD45A1 for that month.

8 Useful Links and Tools

8.1 LP-DAAC Tools

A comprehensive set of tools for handling, converting and reprojecting MODIS products in hdf format is available at:

- https://lpdaac.usgs.gov/tools

9 Frequently Asked Questions

I cannot order the MCD45A1 product for June 2001. Why is it not online?

The MODIS instrument had a prolonged outage in June 2001. As a consequence, not enough input data is available for the production of MCD45A1 for that month.

I downloaded some MCD45A1 data in hdf format. When I open it, I see several layers. Which one shall I start looking at?

For most of the users, the relevant information is the location of the burned pixels, and the day of burning. This data is contained in the first layer (SDS in the MODIS jargon), called 'burndate'.

When I try to open a file in ENVI, I get an error message "unsupported MODIS product"?

You can either open the file as generic HDF with:
File -> Open External Files -> Generic Formats -> HDF
or install the MODIS conversion toolkit from the EXELIS website:
http://www.exelisvis.com/language/en-US/UserCommunity/CodeLibrary.aspx

I received the username and password for the ftp server, I clicked on the link and nothing happens. What shall I do?

FTP servers do not work like normal webpages. You need an ftp client (a list is given in paragraph 4.1) and you need to read careful the documentation of the ftp client to understand how to download data.

10 Citation

The MODIS burned area product, and the details of the algorithm, are described in the following papers. They should be referenced when using the MODIS burned area product:

D.P. Roy, L. Boschetti, C.O. Justice, J. Ju. 2008. The Collection 5 MODIS Burned Area Product - Global Evaluation by Comparison with the MODIS Active Fire Product. *Remote Sensing of Environment*, 112, 3690-3707. (PDF file, 4.5MB)

Roy, D.P., Jin, Y., Lewis, P.E., Justice, C.O. 2005. Prototyping a global algorithm for systematic fire-affected area mapping using MODIS time series data. *Remote Sensing of Environment,* 97:137-162. (PDF file, 4MB)

Roy D.P., Lewis P.E., Justice C.O. 2002. Burned area mapping using multi-temporal moderate spatial resolution data - a bi-directional reflectance model-based expectation approach. *Remote Sensing of Environment*, 83:263-286. (PDF file, 2.3 MB)

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P.J. Zarco-Tejada, C.A. Rueda and S.L. Ustin, "Water content estimation in vegetation with MODIS reflectance data and model inversion methods" *Remote Sensing of Environment*, vol. *85*, pp. *109– 124*, 2003.

Appendix 1

Algorithm Background

12 Algorithm Background

Burned areas are characterized by deposits of charcoal and ash, removal of vegetation, and alteration of the vegetation structure (Roy et al. 1999). The MODIS algorithm to map burned areas takes advantage of these spectral, temporal, and structural changes. The algorithm detects the approximate date of burning at 500 m by locating the occurrence of rapid changes in daily surface reflectance time series data. It is an improvement on previous methods through the use of a bidirectional reflectance model to deal with angular variations found in satellite data and the use of a statistical measure to detect change probability from a previously observed state (Roy et al. 2005). The algorithm maps the spatial extent of recent fires only and excludes fires that occurred in previous seasons or years.

The bidirectional reflectance model-based change detection algorithm developed for the MCD45 product is a generic change detection method that is applied independently to geolocated pixels over a long time series (weeks to months) of reflectance observations (Roy et al. 2002, Roy et al. 2005). Reflectance sensed within a temporal window of a fixed number of days are used to predict the reflectance on a subsequent day. A statistical measure is used to determine if the difference between the predicted and observed reflectance is a significant change of interest. Rather than attempting to minimize the directional information present in wide field-of-view satellite data by compositing, or by the use of spectral indices, this information is used to model the directional dependence of reflectance. This provides a semi-physically based method to predict change in reflectance from the previous state.

12.1 The Bidirectional Reflectance Model-based Expectation Approach

Methods have been developed to model the BRDF with a limited number of parameters and then to estimate the model parameters from a finite set of remotely sensed observations (Lucht 2004). The semi-empirical RossThick-LiSparse reciprocal BRDF model is used for the MODIS global burned area product as it performs robustly in the global MODIS BRDF/albedo product (Schaaf et al. 2002). Like other linear kernel-driven models it allows analytical model inversion with an estimate of uncertainty in the model parameters and linear combinations thereof (Lucht and Roujean 2000, Lucht and Lewis 2000). At each geolocated pixel the three parameter RossThick-LiSparse reciprocal BRDF model is inverted against $m \geq 7$ reflectance observations sensed in a temporal window of n (≥ 16) days duration. The BRDF model parameters are used to compute predicted reflectance and uncertainties for the viewing and illumination angles of a subsequent observation. A Z-score is used as a normalized measure related to the probability of the new observation belonging to the same set as that used in the BRDF model inversion:

$$Z_\lambda = \frac{\rho_{new}(\lambda,\Omega,\Omega') - \rho(\lambda,\Omega,\Omega')}{\varepsilon} \qquad (1)$$

$$\varepsilon = \sqrt{\sigma_\lambda^2 + e^2 \frac{1}{w}}$$

where:

- Z_λ is the Z-score value,
- $\rho_{new}(\lambda,\Omega,\Omega')$ is the new reflectance observation,
- $\rho(\lambda,\Omega,\Omega')$ is the model predicted reflectance at wavelength λ computed by analytical inversion of the BRDF model against previous reflectance observations,
- Ω and Ω' are the viewing and illumination vectors respectively of the new reflectance observation,
- σ_λ is a fixed pre-assigned estimate of the noise in $\rho_{new}(\lambda,\Omega,\Omega')$ defined by Vermote et al. (2002),
- e is the root mean squared of the residuals of the BRDF inversion (used as an estimate of noise in the observations and the lack of ability of the model to fit the measurements), and
- w is the 'weight of determination' of $\rho_{new}(\lambda,\Omega,\Omega')$ (Lucht and Lewis 2000).

Z_λ is adaptive to the viewing and illumination angles of the new observation, as well as the angular distribution, amount of noise, and number of observations used in the BRDF inversion. The Z-score is computed for MODIS bands 2 and 5 as these bands are both sensitive to burning and experience a decrease in reflectance post-fire. A new observation is considered as a burn candidate if:

$$(Z_{band2} < -Z_{thresh}) \text{ OR } (Z_{band5} < -Z_{thresh}) \qquad (2)$$

where:

- Z_{band} is the Z-score defined (1) and
- Z_{thresh} is a fixed wavelength independent threshold

and if:

$$\rho(\lambda_{band5},\Omega,\Omega') - \rho(\lambda_{band7},\Omega,\Omega') > \rho_{new}(\lambda_{band5},\Omega,\Omega') - \rho_{new}(\lambda_{band7},\Omega,\Omega') \qquad (3)$$

AND

$$\rho(\lambda_{band2},\Omega,\Omega') - \rho(\lambda_{band7},\Omega,\Omega') > \rho_{new}(\lambda_{band2},\Omega,\Omega') - \rho_{new}(\lambda_{band7},\Omega,\Omega')$$

where $\rho_{new}(\lambda,\Omega,\Omega')$ is the new reflectance observation and $\rho(\lambda,\Omega,\Omega')$ is the model predicted reflectance computed by analytical inversion of the BRDF model against m $\geq$ 7 previous reflectance observations. The justification for equation (3) is that burning causes a reduction in band 2 and 5 reflectance but less change in band 7 reflectance, whereas persistent cloud, shadow, or soil moisture changes would have a similar effect in both bands. Band 2 helps to remove changes associated with increasing plant water content which is negatively related to band 5 and 7 reflectance but not band 2 reflectance (Zarco-Tejada et al. 2003). In this work Zthresh = 3.0 to detect only those reflectance changes that fall outside of the expected reflectance variation modeled from previous values (the probability that Z < -3.0 is ~0.0013).

12.2 Temporal Implementation

The computation (equations 1-3) is repeated independently for each geolocated pixel, moving through the reflectance time series in daily steps to detect change. A temporal constraint is used to differentiate between temporary changes, such as shadows, undetected residual clouds, soil moisture changes and data artifacts, that pass (1) – (3) from fire-affected areas that have persistently lower post-fire reflectance.

Gaps in the reflectance time series, for example due to cloud cover or bad quality input data, reduce the temporal frequency of Z-score calculations as they reduce the number of observations available for prediction and the number of windows that have sufficient observations for BRDF inversion. To reduce the impact of gaps, the duration of the BRDF inversion window is allowed to increase and the Z-score is computed not just for the subsequent day but for several subsequent days. The duration of the BRDF inversion window is allowed to increase, from a minimum of n = 16 days up to a maximum of ($n + n_{extra}$) days, until there are at least 7 observations. When there are fewer than 7 observations no inversion is performed. In this way, more BRDF inversions may be performed in the presence of missing data, providing more opportunities for detecting burning events. At each window containing 7 or more observations the BRDF parameters are used to compute Z-scores for the non-missing observations sensed on the following S_{search} days. If within the following S_{search} days a burn candidate is found, i.e. criteria (1) - (3) are met, then the Z-scores continue to be computed for S_{test} days after the first burn candidate.

For each inversion window, the day that the first burn candidate was detected (Day_{first}), the maximum of its band 2 and 5 Z-scores (Z_{first}), and the total number of observations over the subsequent S_{test} days that were considered (N_{used}) and detected as burned (N_{pass}), are derived. Different Day_{first} candidates may be detected due to sensitivity of the adaptive window duration and multi-date prediction to gaps in the time series. In addition, the same geolocated pixel may burn on separate dates. The results from the different inversion windows are ranked with respect to N_{pass} and

then N_{used} to provide results in order of the most evidence of persistent burning. If there are results with equal N_{pass} and N_{used} values then the one with the greatest Z_{first} is ranked as more persistent. Searching both forward and backward in time allows burn candidates to be detected in the S_{search} days preceding or following periods of persistently missing data. This also allows burn candidates to be detected in the first and last S_{search} days of the time series. Results for the forward and backward directions are derived independently. When searching backward in time, an increase in reflectance in the appropriate MODIS bands is searched for rather than a decrease in reflectance.

12.2.1 Iterative Procedure for Identification of Burned Candidates

The global algorithm attempts to reduce errors of commission by selecting only burned pixels where there are burn candidates that provide persistent evidence of fire occurrence. As the measured persistence varies depending on gaps in the reflectance time series and the timing of the fire relative to non-missing data, an iterative rather than simple thresholding approach is used. Burn candidates found in both the forward and backward directions are considered.

First, burned pixels are selected as occurring on Day_{first} if:

$$N_{pass} \geq 3 \text{ AND } (N_{pass} / N_{used}) \geq 0.5 \text{ AND } N_{inv} \geq 3 \qquad (4)$$

In this way only candidates are selected, regardless of the direction of the detection, where at least 50% of the observations considered over the subsequent S_{test} days are detected as burned and at least 3 inversions (N_{inv}) are used for the consistency test. If several burn candidates are found at a given pixel, then they are considered in order of decreasing evidence of persistent burning and the first one that passes condition (4) is selected. If forward and backward search results have equal persistence then the forward direction results are given precedence. In cloudy regions, even confidently detected burn candidates might have insufficient data for 3 inversions within the timeframe of the consistency test. As a consequence, if – and only if – backward and forward predict the same change, burned pixels are selected, regardless of N_{inv} using the less restrictive test:

$$N_{pass} \geq 3 \text{ AND } (N_{pass} / N_{used}) \geq 0.5 \qquad (5)$$

Second, rather than discard burn candidates that are likely burned but do not pass conditions (4) and (5) due to insufficient observations, they are considered using less restrictive criteria than (4) or (5) in an iterative search method. This method is based on the principle that there is increasing expectation of a burn occurring in pixels neighboring confidently detected burns (Roy et al. 2002, Graetz et al. 2003). In this search procedure, the burn candidates selected by (4) and (5) are considered seed pixels.

In the first set of iterations, non-seed pixels where burn candidates were detected that did not pass conditions (4) or (5) are accepted as burned if they have two or more adjacent seed neighbors and if:

$$Day_{first} - Day_{first_seed} < N_{gap} \text{ AND } N_{pass} \geq 2 \text{ AND } (N_{pass} / N_{used}) \geq 0.25 \qquad (6)$$

where Day_{first}, N_{pass}, and N_{used} are the values for the burn candidate that did not pass conditions (4) or (5) and Day_{first_seed} is the mean Day_{first} value of the two to eight adjacent seed pixels. The N_{gap} constraint ensures that only burn candidates that occur temporally as well as spatially close to the neighboring seed pixels are considered. This procedure is repeated in an exhaustive iterative manner with the pixels that passed condition (6) being considered as seeds for the next iteration until no more burn candidates that pass (6) can be included. As with condition (4), if several burn candidates are found at a given pixel then they are considered in order of decreasing evidence of persistent burning until (6) is met. Again, if forward and backward search results have equal persistence then the forward direction results are given precedence.

In the second part of the procedure, the residual burn candidates not selected in the previous steps are considered if at least three neighbors have been selected. The average day of burning of the neighbors is computed, and the pixel is accepted if the backward

Appendix 2

Coordinate conversion for the MODIS sinusoidal projection

13 Coordinate conversion for the MODIS sinusoidal projection

Most software packages do not support fully the MODIS projected data; this appendix provides some useful formulas for:

- defining the MODIS map projection and associating a World file to a MODIS tile
- calculating the image coordinates of a geographic point (direct problem)
- calculating the geographic coordinates of a specific point of an image (inverse problem).

The MODIS data are re-projected using an equiareal sinusoidal projection, defined on a sphere of radius

ρ=6371007.181 m,

and with the Greenwich meridian as the central meridian of the projection.

Defining (x, y) as the East and North coordinate in meters of a point in the map space, and (ϕ, λ) its latitude and longitude in degrees, the direct formulas is:

$$x = \rho \cdot \cos\varphi \cdot \lambda \cdot \frac{\pi}{180} \qquad (1)$$

$$y = \rho \cdot \varphi \cdot \frac{\pi}{180} \qquad (2)$$

and the inverse formulas derive from (1) and (2) through simple mathematical passages:

$$\varphi = \frac{y}{\rho} \cdot \frac{180}{\pi} \qquad (3)$$

$$\lambda = \frac{x}{\rho \cdot \cos\varphi} \cdot \frac{180}{\pi} = \frac{x}{\rho \cdot \cos\left(\frac{y}{\rho} \cdot \frac{180}{\pi}\right)} \cdot \frac{180}{\pi} \qquad (4)$$

The range of x and y can be determined easily:

x_{min} = x(ϕ=0, λ=-180) =- 20015109m (5)

x_{max}= x(ϕ=0, λ=180) = 20015109m (6)

y_{min} =y(ϕ=-90, λ=0) = -10007554m (7)

y_{max}=y(ϕ=90, λ=0) = 10007554m (8)

For the distribution of MODIS data, the sinusoidal map space is partitioned into 36 x 18 tiles of fixed location, each of them corresponding to 1200 x 1200 "1km" pixels, or 2400 x 2400 "500m" pixels or 4800 x 4800 "250m" pixels.

Equations 1 and 2 allow the conversion from the geographic space, to the map space. However, to pass from the map space to the image coordinates we need a few more steps. Each pixel is identified not by two, but by four coordinates: (i,j) being the column, row coordinates of the pixel within the tile, and (h,v) being the horizontal and vertical coordinates of the tile.

As 5 though 8 provide the range of x and y, the size *t* of the grid defining the tiles can be calculated as:

$$t = \frac{(x_{max} - x_{min})}{36} = \frac{(y_{max} - y_{min})}{18} = 1111950\ m \qquad (9)$$

Dividing by the number of pixels in each tile, we obtain that the exact pixel size for the level 3 MODIS data:

$$pixel_{size} = \frac{t}{n_{pixels}} \qquad (10)$$

where n_{pixels} ={1200; 2400;4800} is the size in pixels of a tile. For the various MODIS resolutions we obtain:

- 926.625m for the "1km"pixels
- 463.313m for the "500m" pixels
- 234.656m for the "250m" pixels

The formulas that link (h,v,i,j) to (x,y), for a tile of are:

$$h = int\left(\frac{x}{t}\right) + 18 \qquad (11)$$

$$v = 8 - int\left(\frac{y}{t}\right) \qquad (12)$$

$$i = int\left[\frac{\left(x - \frac{t}{2\,n_{pixels}}\right)}{\frac{t}{n_{pixels}}} MOD(n_{pixels})\right] \qquad (13)$$

$$j = int\left[n_{pixels} - \frac{\left(y - \frac{t}{2\,n_{pixels}}\right)}{\frac{t}{n_{pixels}}} MOD(n_{pixels})\right] \qquad (14)$$

The inverse formulas are trivial:

$$x = (i + 0.5)\frac{t}{n_{pixels}} + ht \qquad (15)$$

$$y = (9 - v)t - (j + 0.5)\frac{t}{n_{pixels}} \qquad (16)$$

By using (1) through (4) and (11) through (16) it's possible to perform any conversion between geographic, map and image coordinates for MODIS level 3 data.

13.1 Writing the World file for a MODIS tile

HDF data are not fully supported by most software packages, and the geographic information is easily lost. In order to associate the geographic information to a MODIS tile, or to any raster derived through further process, it is necessary to know the parameters of the projection, the exact pixel size and the coordinates of the corner of the image. It is often necessary to know the coordinates of the corner in the map projection (i.e. x,y in metres) rather than the geographic coordinates.

A widely used format in GIS applications to store the map information is the World File. A world file is a text file containing the pixel size, the rotation information and the coordinates of the upper left corner. The world file has the same name as the file containing the data, and an extension made by the first and third letter of the original extension, plus the letter "w". For instance, 'filename.tif' will be accompanied by 'filename.tfw' and 'filename.gif' will be accompanied by 'filename.gfw'

For a generic MODIS (h,v) tile, the six lines of the world file are:

- line 1: pixel size, from (10)
- line 2: 0
- line 3: 0
- line 4: negative of the pixel size, from (10)
- line 5: upper left x coordinate, from (15) with i=0
- line 6: upper left y coordinate, from (16) with j=0

For example, the world file for tile h08v05 is:

- 463.3127166
- 0
- 0
- -463.3127166
- -11119273.541
- 4447570.423

Appendix 3

Coverage of the Geotiff subsets

Table 1: Regions and bounding coordinates of the Geotiff subsets.

Window #	Coverage	Min Lon	Max Lon	Min Lat	Max Lat
1	Alaska	-180	-140.5	50	70
2	Canada	-141.5	-50	40	70
3	USA (Conterminous)	-125	-65	23	50
4	Central America	-118	-58	7	33
5	South America (North)	-82	-34	-10	13
6	South America (Central)	-79	-34	-35	-10
7	South America (South)	-77	-54	-56	-35
8	Europe	-11	35	33	70
9	West and North Africa	-19	5	0	37.5
10	Central and North Africa	5	25	0	37.5
11	East Africa and Arabian Penisula	25	65	0	37.5
12	Southern Africa (North)	8.5	48	-15	5.5
12B	Tanzania	29.5	40.6	-12	-0.6
13	Southern Africa (South)	10	41	-35	-15
14	Madagascar	42	59	-27	-10
15	Russia and Central Asia 1	35	90	33	70
16	Russia and Central Asia 2	90	145	33	70
17	Russia (Kamachatka)	145	180	40	70
18	South Asia	60	93	5	36
19	South East Asia	90	155	-10	33
20	Australia	112	155	-45	-10
21	New Zealand	165	179	-48	-33
22	Azores	-31.6	-24.8	36.8	40
23	Cape Verde Island	-25.5	-22.5	14.6	17.5
24	Hawaii	-161	-154	18	24

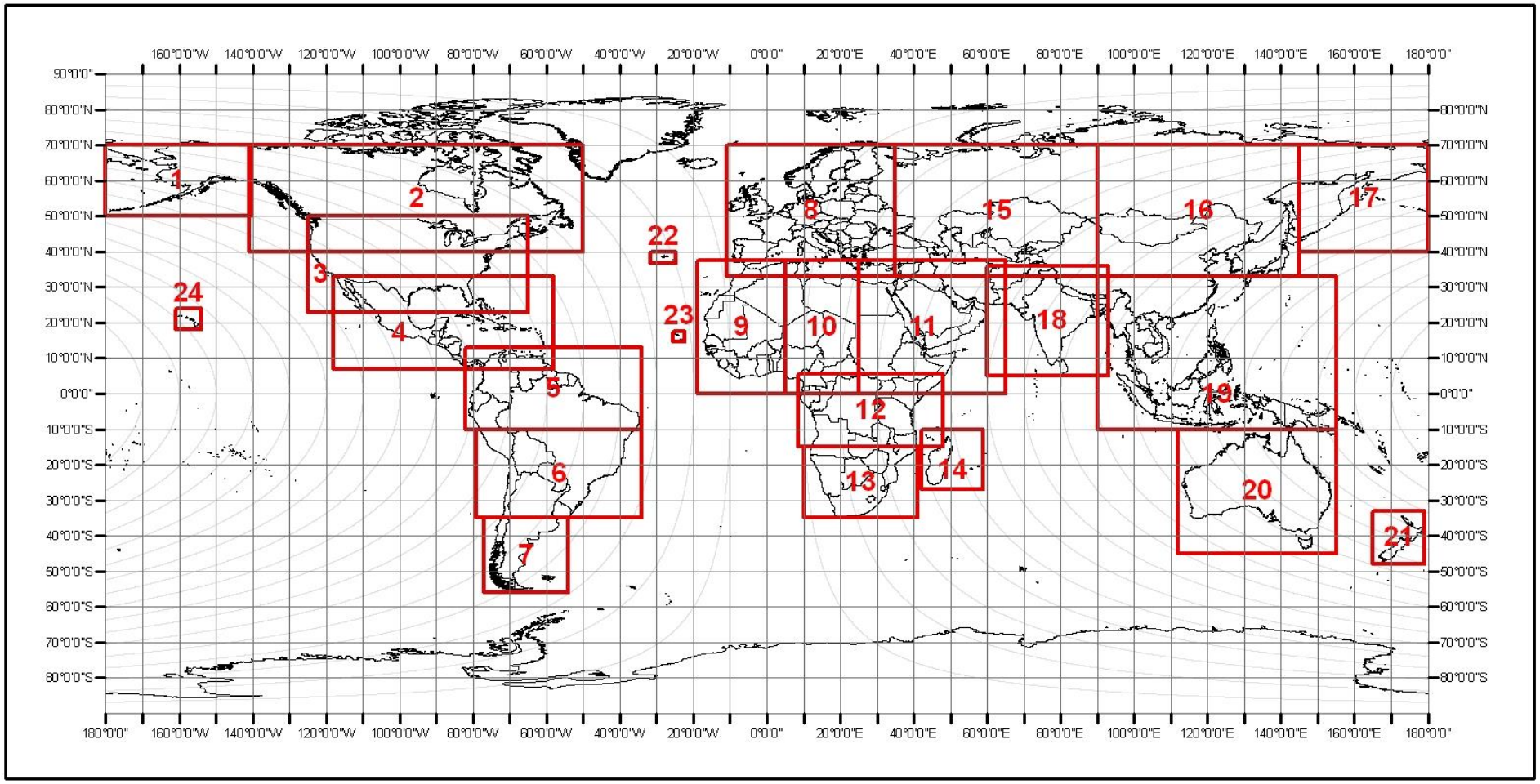

Figure 6: Coverage of Geotiff subsets