Burnt area detection at global scale using ATSR-2: The GLOBSCAR products and their qualification

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[1] Quantifying the contribution of biomass burning to the global distribution of emissions of carbon into the atmosphere requires knowledge of the area burnt. The GLOBSCAR project was initiated in 2001 as part of the European Space Agency (ESA) Data User Programme, with the objective of producing global incremental monthly maps of burnt areas, using daytime data from year 2000 of the Along Track Scanning Radiometer (ATSR-2) instrument onboard the ESA ERS-2 satellite. The processing system combines the use of two algorithms representing different approaches to burnt area detection. The K1 algorithm is a contextual algorithm based on the geometrical characteristics of the burnt pixels in the near-infrared (NIR, 0.87 microns)/thermal infrared (TIR, 11 microns) space, while the E1 algorithm consists of a series of fixed threshold tests applied to the data using information from four different spectral channels. The GLOBSCAR products are available from the GeoSuccess Web site (http://www.geosuccess.net) in ASCII and vector format. The products were validated using a variety of qualitative and quantitative tests against other field and remote sensing data. The GLOBSCAR results are presented per region and are compared to available statistics and other remote sensing products such as the ATSR-2 World Fire Atlas (WFA) and the Global Burnt Area product derived from SPOT/VEGETATION (GBA-2000). The potential and limitations of the GLOBSCAR products are then discussed. It is concluded that while the GLOBSCAR products represent a definite progress toward a better quantification of the areas burnt annually at the larger scales, coordinated improvements in remote sensing products are needed in order to better address the requirements of the user community. Future activities include the consolidation of the results through further qualification and the development of a multiyear multisensor product building upon the experience gained from both GLOBSCAR and GBA-2000 projects. *INDEX TERMS:* 1610 Global Change: Atmosphere (0315, 0325); 1640 Global Change: Remote sensing; 1694 Global Change: Instruments and techniques; 1699 Global Change: General or miscellaneous; *KEYWORDS:* global, burnt area, verification, GLOBSCAR, satellite, ATSR-2

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1. Introduction

1.1. Scientific Background

[2] Vegetation fire events occur in many regions of the globe throughout the year, with environmental impacts at various levels. Their contribution to the emission of gases and aerosols into the atmosphere has been recognized and documented [*Levine*, 1991; *Crutzen and Goldammer*, 1993; *Levine et al.*, 1999]. For this reason the scientific communities dealing with modeling of emissions from biomass burning require better quantitative estimates of the biomass burnt at a global scale.

[3] According to *Seiler and Crutzen* [1980], the quantity of biomass burning can be expressed as a function of biomass density, fraction of biomass over the ground with respect to the total biomass, burning efficiency, and area burnt. This last variable does not require a priori study and can be evaluated interactively with the proper tools. According to *Levine* [1996], the accurate assessment of the spatial and temporal distribution of burning is the greatest challenge faced by the scientific community studying biomass burning. Remote sensing can play an essential role in this evaluation [*Chuvieco and Martin*, 1999], especially for studies over large areas, owing to its global coverage capability and frequent revisiting period.

[4] In recent years, several projects have been initiated to produce global inventories of active vegetation fires using remote sensing [*Arino and Rosaz*, 1999; *Stroppiana et al.*,

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2000]. However, although providing information on the spatial and temporal distribution of the fires, these inventories fail to quantify the extent of the areas burnt.

[5] Despite the number of analyses on the differentiation of burnt areas in a number of specific regions [*Arino et al.*, 2000; *Stroppiana et al.*, 2002; *Trigg and Flasse*, 2000], to date there is no clear consensus on an automated method capable of identifying these surfaces at a global scale without reference to a particular zone (e.g., boreal or tropical) or vegetation type (e.g., savannah or forest).

1.2. Project Framework

[6] During a meeting held in Ispra, Italy, in November 1999, the fire component of the Global Observation of Forest Cover/Global Observation of Land Dynamics project (GOFC/GOLD), *Ahern et al.* [2001, p. 8] recommended "the initiation of [...] a 1-km resolution global area burned product" in response to the need for better estimates of the areas burnt at global scale.

[7] A number of algorithms were then studied under the European Space Agency (ESA) announcement of opportunity (AO) 329 on the "Development and testing of algorithms for a global burnt area (GBA) product from ERS-2 ATSR-2" [*Piccolini*, 1998; *Piccolini and Arino*, 2000]. Partners of this work were the Department of Forestry of the Instituto Superior de Agronomia (DEF/ISA, University of Lisbon), the Global Vegetation Monitoring Unit at the Institute for Environment and Sustainability (GVM/IES), and ESA. The algorithms under evaluation used various methods including the multitemporal and contextual analysis of spectral bands or derived indices and thresholding tests over multiple bands. Out of the ten algorithms developed and tested, only two were retained as viable for application at global scale, in view of their performance in different types of ecosystems.

2. The GLOBSCAR Project

[8] Building upon these algorithms, the GLOBSCAR project was initiated under the ESA Data User Programme (DUP) and was run from November 2000 to December 2001 through a contract with the Flemish Technological Research Institute (VITO). The objective of the project was to demonstrate the feasibility of the processing, production, and distribution chain of a global burnt area product on a regular basis and within a timely framework on the basis of Along Track Scanning Radiometer (ATSR-2) data and using algorithms already identified. The year 2000 was chosen to allow intercomparison with other global burnt area products such as the GBA-2000 product developed by the Global Vegetation Monitoring Unit at the Joint Research Center (JRC) in Ispra, Italy, together with a number of international partners [*Grégoire et al.*, 2003] and also products from the NASA Moderate-Resolution Imaging Spectroradiometer (MODIS) instrument.

2.1. ATSR-2 Daytime Data

[9] The data chosen for the GLOBSCAR project were those acquired with the ATSR-2 instrument on board the ESA ERS-2 satellite. Daytime imagery from this instrument is appropriate for a number of reasons. First, a near-infrared (NIR; 0.865 microns) and a thermal infrared (TIR; 10.9 microns) channel are available on ATSR-2, both at high spectral resolution. These are the most useful spectral bands for global burnt area detection [*Arino et al.*, 2000; *Stroppiana et al.*, 2002; *Trigg and Flasse*, 2000]. The presence of a TIR is a particularly valuable asset compared to other optical sensors such as SPOT-VEGETATION. The other bands available are two visible channels at 0.555 and 0.659 microns, a shortwave infrared (SWIR) and a MIR channel (1.6 and 3.7 microns, respectively) and one additional TIR band at 12 microns [*Mutlow et al.*, 1999].

[10] Second, the repeat cycle (35 days) of the ERS-2 satellite combined with the ATSR-2 swath (509 km) allow the same point on the Earth surface to be observed at least every 3 days at the equator. *Eva and Lambin* [1998] defined 17 days as the upper limit for accurate detection of burnt areas in tropical savannas, the ecosystem with most rapid regrowth. A revisit period of 3 days should give therefore at least 5 opportunities to see an area affected by fire, which is acceptable even in the case of frequent cloud coverage. Finally, the daytime overpass of 10:30 at the equator is appropriate since at this time the ground already shows its characteristics in terms of heat exchange, but the formation of clouds owing to the water surface evaporation is still limited.

[11] The ATSR-2 products used were the SADIST level 1B products [*Bailey*, 1995], which are calibrated and geolocated top-of-atmosphere (TOA) gridded brightness temperature (GBT) and reflectance images of 512×512 pixels. The instantaneous field of view provides a pixel at nadir with a resolution of 1 km in the seven channels. The reduced field of view across the path (509 km swath) means that the ground area associated even with edge pixels is close to a square area of 1×1 km. The instrument exhibits a very high multispectral registration accuracy of better than 1/10 of a pixel, while the absolute geolocation accuracy is in the order of 1 km in nominal conditions. In 2000, however, the operation of the ERS-2 satellite in monogyro mode degraded slightly the multitemporal registration accuracy, to $\sim$2 km.

2.2. Method

[12] The GLOBSCAR algorithm is a blend of two algorithms developed and tested within the AO 329 mentioned above. These algorithms are now presented in more detail.

2.2.1. K1 Algorithm

[13] *Piccolini* [1998] developed this algorithm using the NIR and TIR spectral channels. The algorithm first exploits the fact that healthy vegetation shows higher reflectance in the NIR than other natural surfaces [*Tucker and Sellers*, 1986; *Pereira and Setzer*, 1993; *Pereira*, 1999]. The second physical characteristic used is the increase of temperature that occurs over a burnt surface during daytime, owing to strong solar irradiance absorption and the absence of evapotranspiration that normally transfers energy to the atmosphere in form of latent heat through water vapor. The presence of ash and carbon constitutes a dry layer that prevents the cooling process, increasing the surface temperature by around 7–8 K [*Lambin and Erlich*, 1996].

[14] The definition of the scalar parameter K1 is based on the geometrical characteristics of the burnt surface pixels in the scatterplot between NIR and TIR value. The burnt pixels move away from the total distribution, as illustrated in

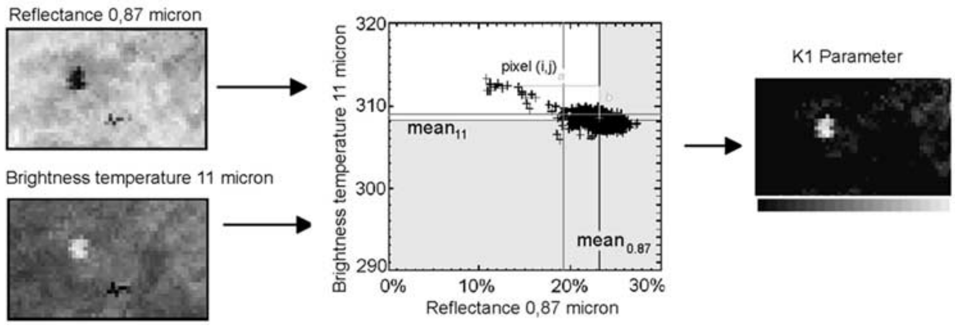

Figure 1. Behavior of burnt surface pixel in the NIR/TIR scatterplot. The pixels that correspond to burned surface move away from the total distribution in the upper left direction. This is due to the increase in temperature and decrease in the NIR reflectance.

Figure 1, exhibiting higher brightness temperature and lower NIR reflectance, independently from the vegetation type or atmospheric status. A third channel traditionally used in burnt area detection is the SWIR channel. However, unlike for the NIR and the TIR channels, the signature of burnt areas in this spectral region depends upon the type of vegetation affected by the burning [*Arino et al.*, 2000], which makes it less appropriate for an algorithm applied systematically at global scale. For this reason the option of adding a new dimension to the K1 algorithm using the SWIR channel was rejected.

[15] The definition of K1 is directly linked to the signal response of burnt surfaces, therefore adopting an adaptive method decorrelated from the possible daily variations (atmospheric, solar illumination, etc). Specifically, the K1 parameter is proportional to the geometrical distance calculated in the NIR-TIR scatterplot, between the point analyzed and the point defined from the means of NIR and TIR of the image under analysis, according to the following equation:

$$\mathrm{K1}(i,j) = \mathrm{mean(NIR)} - \mathrm{NIR} + 2 \times \mathrm{TIR} - 2 \times \mathrm{mean(TIR)} - \mathrm{var(TIR)}, \quad (1)$$

where TIR, mean(TIR), and var(TIR) are expressed in Kelvin, while NIR and mean(NIR) are the integer expression of the actual percentages (e.g., 40% reflection will be translated into NIR = 40 in the formula).

[16] The K1 algorithm is applied on windows of a fixed size set as a parameter of the processing. The size chosen for the project was 50 × 30 km. This size reconciles the need for a sufficiently homogeneous window in terms of land cover and the need for a sufficient number of pixels to derive the mean quantities used in the processing.

[17] The mean and variance values needed are calculated for all the windows of the entire GBT product. The mean and variance values used for the calculation of the K1 value within a particular window are derived from the bilinear interpolation of the mean and variances of its neighbor windows. This is done to avoid a chess pattern in the output product. Nonburnable pixels are not used for the calculation of the mean and variance quantities, and windows containing nonburnable pixels only do not contribute to the interpolation.

[18] Furthermore, K1 is only calculated for potentially burnt pixels according to the expected variations in the NIR-TIR space; that is, pixels showing values of NIR and TIR such that:

$$[\mathrm{NIR} < \mathrm{mean(NIR)}] \text{ and } [\mathrm{TIR} > \mathrm{mean(TIR)} + 0.5 \times \mathrm{var(TIR)}]. \quad (2)$$

K1 can therefore only take positive values, and its value increases as the contrast between burnt and nonburnt pixels in the NIR-TIR space increases. The original detection criterion as designed by *Piccolini* [1998] used a Bayesian formula for the probability of a pixel to be burnt. However, a thorough analysis of these probabilities has shown that setting a threshold on the probability of burnt area for a given K1 value is equivalent to setting a threshold on the K1 value, as the probability is an increasing function of K1.

[19] Testing by VITO in different ecosystems and seasonal conditions has led to the following criterion for burnt area detection: a pixel is identified as burnt if

$$K1 > 10.5. \quad (3)$$

This threshold is a compromise for global applications, limiting the risk of systematic omissions in some ecosystems but inducing some commission errors in other areas. In order to obtain acceptable results globally, the K1 algorithm cannot be applied as a stand-alone algorithm but must be combined instead with a series of complementary threshold tests such as those used by the E1 algorithm.

2.2.2. E1 Algorithm

[20] The E1 algorithm [*Eva and Lambin*, 1998; H. Eva, personal communication, 2000] consists of a set of fixed threshold tests on ATSR-2 data that were initially designed for application over tropical savannas, especially sub-Saharan northern Africa and South America. For a pixel to be accepted as burnt by the E1 algorithm, it must satisfy the following tests: (1) $\mathrm{RED}_{0.67\mu} < 10\%$; (2) NDVI < 0.4 (3) $\mathrm{SWIR}_{1.6\mu} < 20\%$; (4) NIR < SWIR; and (5) $\mathrm{BT}_{11\mu} > 300$ K.

[21] The normalized differential vegetation index (NDVI) is defined by

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{RED})/(\mathrm{NIR} + \mathrm{RED}). \quad (4)$$

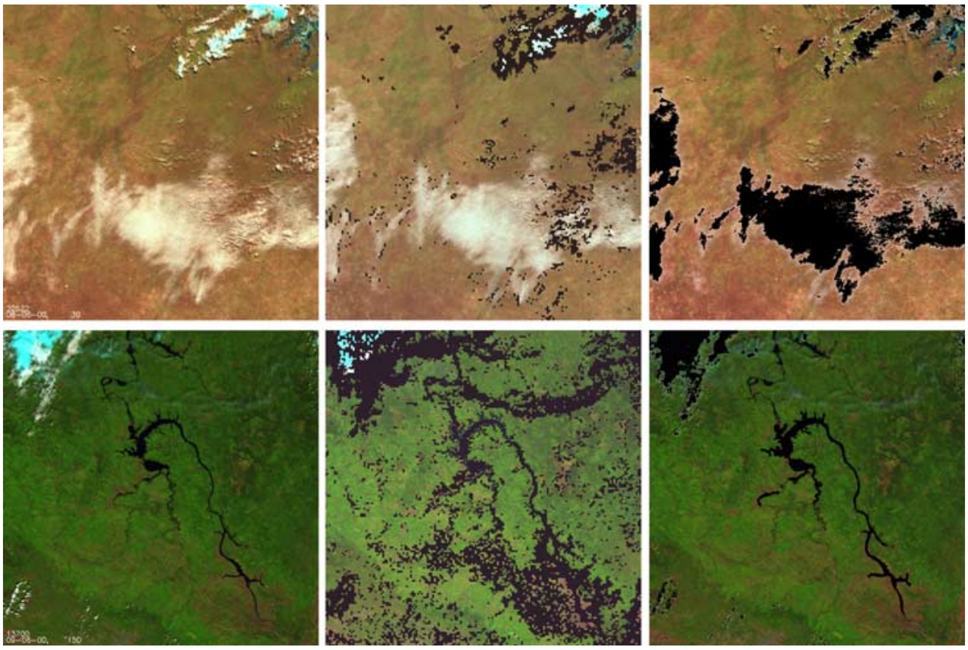

Figure 2. Examples of the new cloud detection scheme over (top panels) Kalahari and (lower panels) Siberia. The images displayed show the (left) original ATSR-2 image, (center) the results obtained from ATSR-2 built-in cloud detection, and (right) the results of the GLOBSCAR cloud detection scheme. Pixels detected as cloudy are shown in black. Water pixels are masked out and for that reason are also shown in black in the image.

As with the K1 algorithm, the E1 algorithm presents a number of limitations when applied at global scale and for this reason cannot be used in a stand-alone configuration.

2.3. Processing System

[22] In the processing system developed by VITO, K1 and E1 algorithms are applied in parallel to every burnable pixel of the ATSR-2 GBT data. The selection of burnable pixels is made using information from a global Plate Carrée projection of the land cover classification map from the International Geosphere-Biosphere Program (IGBP) [*Loveland et al.*, 2000]. Pixels belonging to nonburnable classes according to the IGBP classification (i.e., water bodies, urban and built-up areas, snow, ice, and barren areas) are eliminated from further processing on the basis of the nearest neighbor information in latitude/longitude. The IGBP classification is therefore only used to exclude nonburnable areas.

[23] Every pixel detected as burnt by both algorithms (and scheme) is then stored in an intermediate ASCII file, with associated information such as the position (in Interrupted Goode Homolosine projection), the date of detection, the K1 value obtained, and the vegetation class.

[24] Individual detections are appended to that intermediate file until the last GBT product of the month is processed. Then a merging step removes the redundancy owing to the concatenation of the detections, which can cause multiple detections of the same pixel within the month. The number of detections and the number of cloud-free observations are kept in the confidence information. Finally, the burnt area products of two consecutive months are compared in order to produce one final incremental product retaining the new burnt areas only. With this option, areas that remain detectable for several months will appear only once in the first month they are detected since comparing two consecutive months will remove those detections from subsequent products.

[25] The processing chain has the capability of processing 1-year worth of ATSR-2 daytime land data, which amounts to ~600 Gb, in ~1 month. The modularity of the implemented processing chain further allows an easy replacement of individual software modules (e.g., improved detection algorithms), as long as these are based on the same general detection approach; namely, nontemporal change detection in the reflectance and brightness temperature of the GBT products.

[26] The risk of confusion between clouds and burnt areas is generally very low owing to contrasting spectral characteristics, especially in the NIR spectral domain. However, since the K1 algorithm uses mean spectral quantities on a window basis, it is important to eliminate cloudy pixels when computing these mean quantities, so that a bias is not introduced in the results. The ATSR-2 built-in cloud detection scheme was originally designed for sea applications, and for that reason it is not reliable over land. As a consequence, a simple improved version algorithm [*Fierens*, 2002] was proposed and implemented for use within the project. It is a subselection of the tests used for the MODIS sensor [*Ackerman et al.*, 2002], focused on the regions of interest for burnt area detection (land pixels only, daytime, no polar regions) and on the available bands in ATSR-2. A pixel was declared cloudy if it fulfilled any of the following conditions: (1) $BT_{11} - BT_{3.7} < -14$ K, (2) $RED_{0.670} > 0.18$, or (3) $0.9 <$ ratio $NIR/RED < 1.1$.

[27] The tests are relatively simple but seem to work reasonably within the limits listed above. Figure 2 shows

some results obtained, in this case over the Kalahari and Siberia. On these examples the GLOBSCAR scheme is an obvious improvement over land compared to the original algorithm. However, significant testing has not been conducted on the efficacy of the mask, and it is likely that there are instances of both overdetection and under-detection. Still, the objectives of the cloud masking were mainly driven by the necessity to exclude cloudy pixels from the calculation of burn thresholds, and therefore the influence of a small amount of cloud entering the burnt area algorithm is not necessarily significant.

[28] With respect to cloud shadow detection, with the (E1 AND K1) scheme, false detection of cloud shadows almost never occurs. Although cloud shadows usually have a low response in the NIR, similar to burnt areas, they tend to have lower values in the thermal channel used in K1 algorithm, contrary to burnt areas. The risk of confusion between cloud shadows and burnt areas is therefore quite low, especially when using the two algorithms E1 and K1 in combination. No cloud shadow detection was therefore implemented within the processing system. It is acknowledged that cloud shadow is a traditional source of problems for burnt area detection, but this is mostly because usually the sensors used for the detection do not have a TIR channel available to make this distinction.

2.4. Output Products

[29] In accordance with the user requirements initially expressed by GOFC/GOLD-Fire, the products developed and proposed under the GLOBSCAR project have the following information content:

[30] 1. They are monthly incremental global products, providing the newly detected burnt areas in a given month.

[31] 2. They cover the entire globe.

[32] 3. They comprise a complete year; in this case, 2000.

[33] The GLOBSCAR end products are available in several formats in order to accommodate the needs of a large number of users and applications.

2.4.1. The Raster Product

[34] The first type of product is a raster image, in portable network graphic (PNG) format, whose role is to provide a quick visualization of the distribution of the areas burnt monthly at global scale. This product is not truly representative of the actual results since one pixel on a quick look corresponds to $\sim$1000 km^2 at the equator (less at higher latitudes). Burnt areas tend therefore to be overrepresented, but it is nevertheless a useful visualization tool for quick inspection of spatial and temporal trends at the larger scales, in a similar way to the quick looks also provided with the ATSR-2 fire atlas products (http://earth.esa.int/ionia).

2.4.2. The ASCII Product

[35] The ASCII format is the main format of distribution. The objective was two-fold when choosing this format: First, to keep the monthly products to an acceptable size ($\sim$2 Mb per monthly file) and second, to provide the products in a format similar to the format adopted for the ATSR-2 fire atlas to facilitate the ingestion of these new products by the ATSR-2 active fire product user community. Table 1 describes the precise format of the products: one line per square kilometer pixel detected as burnt, with the date of the first detection (one pixel may be detected several times as burnt within the same month) and its geographic coordinates in latitude and longitude. Since no reliable contemporary land cover classification product existed at the time of the project, no vegetation type information is attached to the GLOBSCAR products. However, this kind of information can easily be retrieved based on the coordinates of the pixels.

Table 1. Format Description for the GLOBSCAR Monthly ASCII Files

Field Name	Format	Description
Date	10 characters (yyyy/mm/dd)	date of first detection
Latitude	8 characters (s999.999)	(s: sign)
Longitude	8 characters (s999.999)	(s: sign)
EOL	2 characters (\r\n)	carriage return line feed

2.4.3. The Vector Product

[36] Finally, the GLOBSCAR products are also provided in vector Shapefile format to facilitate their ingestion in Web map or Web feature servers. The initial objective when selecting this format was also to reduce the final size of the monthly products since adjacent pixels form one unique polygon. In the end though, owing to the scattered nature of the burnt areas, there are large numbers of isolated pixels. As a result, vector format is less appropriate in this specific case (larger size, typically 15 Mb per month).

2.4.4. Distribution

[37] The GLOBSCAR products are available, in all described formats, from the Geosuccess Web site hosted by VITO (http://www.geosuccess.net). After registering into the Web site, users are provided a password that they can use to access via FTP all products available from the Web site, and in particular the GLOBSCAR products.

[38] The raster quick looks are also available from the Ionia Web site (http://earth.esa.int/ionia), which distributes the ATSR-2 monthly active fire products. Finally, the GLOBSCAR burnt areas form one of the layers available from the ESA Web map server hosted at ESA (http://mapserv2.esrin.esa.it/map/wtf/). Several other layers such as the active fires from ATSR-2, the IGBP land cover classification, or the rainfall make this map server a powerful tool for intercorrelation studies and visual analysis of the results in specific areas. The map server is OpenGIS compatible. Figure 3 shows an example of the potential of the ESA map server, here in the case of a large burning event that took place in September 2000 in the Kruger National Park, South Africa. According to the IGBP classification, the vegetation affected was a mixture of cropland (class 12) and savannah (class 9). The overall area affected amounts to $\sim$80,000 ha.

2.5. Qualification Process

[39] The qualification of the results obtained was performed in two phases. A general validation exercise was carried out by VITO followed by an additional internal qualification exercise coordinated by ESA.

2.5.1. Product Validation

[40] A general validation exercise was performed by VITO within the contractual framework of the project. VITO applied a single systematic analysis method for all validation data to allow for consistency in the analysis of the results. A number of measurable quantities were introduced to evaluate the quality of the results obtained. These included the rates of omission/commission, the consistency

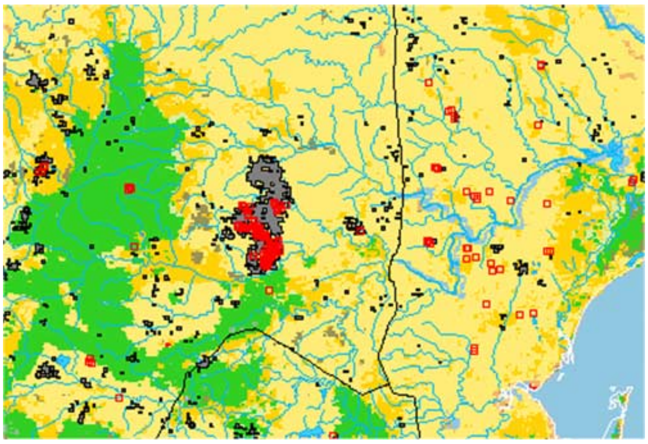

Figure 3. Example of results obtained using the ESA web map server (WMS) over the Kruger National Park, South Africa, in September 2000. The various layers displayed include the IGBP land cover classification, political boundaries and country borders, rivers and lakes (National Imagery and Mapping Agency), ATSR-2 fires (red squares), and GLOBSCAR burnt areas (black polygons with shading).

between the two algorithms and the duration of burnt area detection. All statistics were then evaluated for each validation data set available. The validation data were provided to VITO by ESA through its validation partners. These included the Joint Research Center at Ispra and the GBA-2000 project partners, the Italian Corpo Forestale dello Stato (CFS) and the French and Italian Civil Protection Authorities, the Food and Agriculture Organization (FAO), U.S. Department of Agriculture Forest Services, the Brazilian Environmental Agency (IBAMA), the Russian Forest Institute (IFI), the Kruger National Park in South Africa, the Australian Department of Land and Administration (DOLA), UTL Lisbon, and University of California, Santa Barbara (UCSB). The validation data set consisted mainly in high-resolution information (~20 classified Landsat TM scenes and burn scar vector files from field measurements), which was made available for several countries of Africa (Central African Republic, Madagascar, Mozambique, Sierra Leone, South Africa, and Zimbabwe), Europe (Portugal, France, Greece, and Italy), Australia, western Russia, and the western United States. This was complemented with national statistics for a number of countries. The quality of the validation data used was evaluated (data source, data type, etc.) and was taken into account for the final validation results. The conclusions from this analysis are presented in the project final report (see the ESA DUP Web site at http://www.esa.int/dup/projects/summaryp24.asp).

[41] The validation exercise showed that the coarse product quality combined with a limited geolocation accuracy in 2000 result in poor quantitative results at local scale which are not necessarily representative of the products performance at larger scale. This is particularly true for smaller fires. As a result, the systematic quantitative analysis performed initially as part of the project is not the best way to report on the intrinsic assets and limitations of the actual products. Instead, qualitative analysis seems a better way of evaluating the quality of this type of global low-resolution products.

2.5.2. Internal Qualification

[42] The project validation exercise was followed by an additional internal qualification performed by ESA. The objective was to get a more general picture of the strengths and weaknesses of the products, particularly in areas where validation data was not available for the validation exercise performed by VITO. In addition to a general review of the results, a dedicated effort was made to intercompare GLOBSCAR with results from other remote sensing fire products (in particular, the ATSR-2 World Fire Atlas (WFA) for active fires and GBA-2000 products for burnt areas) in order to provide users of those products with a better view on how they intercompare. This internal review was complemented by reports from additional validation partners willing to make their own evaluation of the products in their area of interest and finally by reports of beta users testing the data for their own application purposes and providing some feedback on the results obtained. The results of this qualification exercise are presented in a qualification report document [*Simon*, 2002], which is available from the Geosuccess and Ionia Web sites.

3. Results

3.1. Global Figures

[43] For this review the main land cover distinction performed is between forested and nonforested areas, where forested areas are defined as areas corresponding to classes 1–5 of the IGBP land cover map [*Loveland et al.*, 2000]. These forested areas are shown in Figure 4. It was considered preferable to avoid detailed systematic analysis per type of vegetation because of the limited spatial and temporal consistency between the GLOBSCAR products and any existing land cover classification available at the time of the project (IGBP and Maryland classifications [*Hansen et al.*, 2000] are both based on the 1992–1993 1 km advanced very high resolution radiometer DISCOVER data set). However, when relevant, some general indications are provided with reference to the IGBP vegetation classes.

[44] The total GLOBSCAR results indicate annual biomass burning figures of ~200 million hectares globally, out of which 30.7 million hectares are over forested areas. For comparison, the average annual burning is estimated at

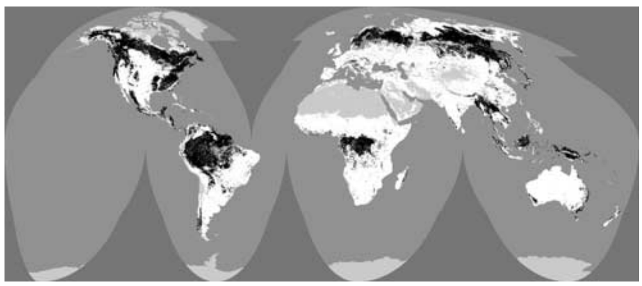

Figure 4. Global distribution of the vegetated areas according to IGBP land cover classification, split into forested (classes 1–5, in black) and nonforested areas (classes 6–12, 14, in white). Nonburnable areas (classes 13, 15–17) are shown by shading.

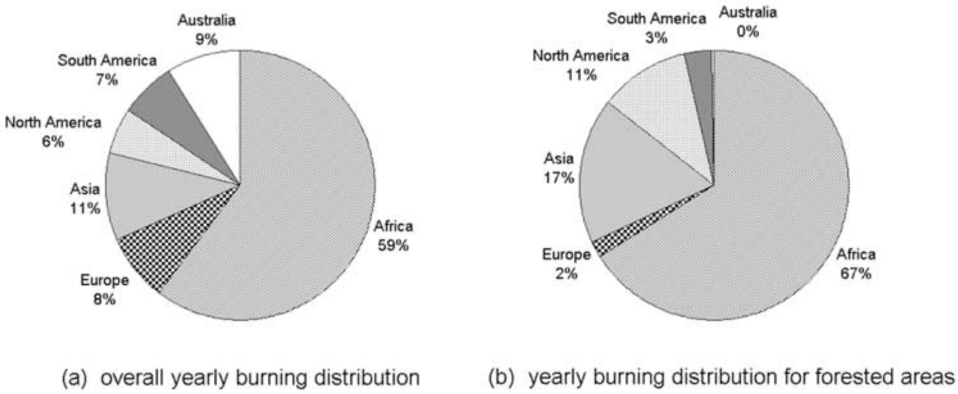

Figure 5. Overall repartition of the burning per continent according to GLOBSCAR results for (a) all vegetated areas and (b) for forested areas only. The biomass burning over Russia is distributed between the European and Asiatic continental figures.

around 500–560 million hectares globally by *Levine et al.* [1999], distributed between 10 and 15 million hectares for temperate and boreal forests, 20–40 million hectares for tropical forests, and 500 million hectares for savannas and woodland. The GLOBSCAR burning over forested areas is therefore within the estimated annual range of 30–55 Mha, while the remaining 170 Mha burning over nonforested areas is a factor of 2–3 below the expected figures.

[45] The distribution of the yearly burning per continent in 2000 is shown in Figure 5, both for the overall figures and for forested areas only. Africa makes the highest contribution with 59% of the overall burning. All other continents make contributions in the range 8–10% to the overall annual burning. Looking at the distribution of the burning over forested areas, the African forests make an important contribution owing to the large burning in Democratic Republic of Congo (DRC), Angola, Tanzania, and Zambia. Instead, the Brazilian forests make a surprisingly small contribution with only 3% of the total burning. A possible explanation for the low figure over Brazil is proposed later in this paper. The important contribution of the Asian continent corresponds to the large biomass burning recorded over the forests of the Russian Federation.

[46] Results from GLOBSCAR, the ATSR-2 WFA, and GBA-2000 can be compared over the various regions and periods of the year. The seasonal spatial distribution of the areas affected by fires according to the three products is illustrated in Figure 6. It should be noted that the scattered nature of the GLOBSCAR products can result in an excessive contribution of the burnt pixels in the quick looks; in some places, this can wrongly display the areas detected by GLOBSCAR as larger than those of GBA-2000.

[47] The three products show roughly similar seasonal distributions of the fire-effected regions throughout the year. The continent with most similar patterns is Africa. The most notable differences between the two burnt area products reside in North America, with a much larger late spring burning recorded by GLOBSCAR than GBA-2000, with no corresponding active fires in the WFA, and in South America, where the burning results of GLOBSCAR are again larger throughout the year compared to GBA-2000 but this time with corresponding fire activity recorded by the WFA.

[48] The major difference between the WFA and both burnt area products is situated in central Europe over the April–June period. There the large areas detected as burnt are not reflected by any significant nighttime fire activity, as recorded by WFA. All these differences are further investigated within the regional review that follows.

[49] The 20 countries presenting the largest burnt areas in 2000 according to GLOBSCAR are listed in Table 2. The percentage of area burnt is indicated, as well as the ranking of those countries by GBA-2000 and WFA and WFA/GLOBSCAR and GLOBSCAR/GBA-2000 ratios. More than half of these countries are African countries. The remaining ones are the large countries such as Russia, Canada, Brazil, the United States, or Australia. The presence of Ukraine and Kazakhstan in the list is due to the large burning figures recorded by GLOBSCAR in spring, which are further discussed in the regional analysis.

[50] The first nine countries according to both GLOBSCAR and GBA-2000 are the same, although in a slightly different order. According to GLOBSCAR, these countries contribute to 70% of the total burning.

[51] Instead, out of the first 20 countries for WFA, 12 are ranked in the first 20 countries for GLOBSCAR and 16 in the first 30. The general repartition of the burning is therefore broadly comparable according to the three products, with a more limited consistency between the active fire product and both burnt area products.

[52] Some countries such as Iran, Iraq, and Algeria have a high ranking according to WFA. These countries have a very low ranking instead, according to both GLOBSCAR and GBA-2000 results. These are clear examples of the detection of nonvegetation fires by the WFA (with, e.g., the detection of gas flares).

3.2. Africa

3.2.1. General Figures

[53] Africa is the continent most affected by burning, with a total area of around 121 Mha affected by fires throughout the year, out of which ~17% are situated in forested areas. For comparison, *Scholes et al.* [1996] estimate the average annual burning in Africa at around 168.4 million hectares,

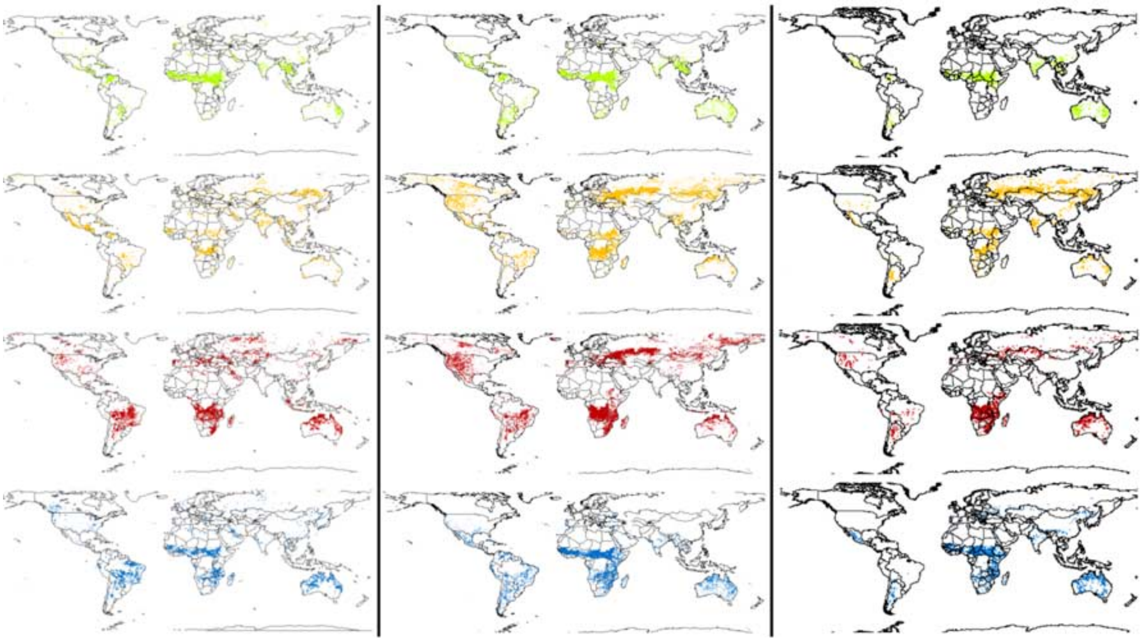

Figure 6. Quick looks of the results obtained by (left) the ATSR world fire atlas, (center) GLOBSCAR, and (right) GBA-2000 results in 2000 presented by 3-month period: January–March, April–June, July–September, and October–December. The GBA-2000 results were visualized using the GBA2000 Web map server hosted at UNEP-GRID (http://www.grid.unep.ch/activities/earlywarning/preview/ims/gba/). The pixel resolution is therefore not exactly the same in the two burnt area products.

while according to *Barbosa et al.* [1999], it amounts to ∼154 million hectares burnt annually. The GLOBSCAR results are therefore on average lower by a factor of 1.2–1.4 compared to average annual figures found in the literature. The annual results of GBA-2000 over Africa are almost a factor of two larger than those of GLOBSCAR, with more than 223 million hectares burnt annually.

[54] For the African countries largely affected by fires (Democratic Republic of Congo, Angola, and Zambia for southern Africa and Sudan, Central African Republic, and Ethiopia for sub-Saharan northern Africa), the amount burnt represents a sizable percentage of the surface area of the country, from 4% up to 15% (in Central African Republic). The majority of the fires affect savannas, grassland, and open shrubland types of vegetation, which exhibit a high fire return frequency.

[55] The first 12 countries affected by burning in Africa are the same for both GBA-2000 and GLOBSCAR, although in a different order, and with an average factor of two difference in the total areas burnt according to both

Table 2. Annual Burning Figures for the 20 Highest Burning Countries, and Intercomparison With WFA and GBA-2000 Results

	Area Burnt, km^2	Ranking WFA	Ranking GBA	Percentage WFA/GLOBSCAR	Percentage GLOBSCAR/GBA
RDC	216,814	6	4	1.3	83.29
Sudan	213,154	4	2	1.8	52.66
Russia	199,897	2	5	5.5	89.30
Australia	180,130	1	1	7.8	32.19
Angola	157,031	16	3	0.9	53.02
CAF	97,272	9	6	1.8	52.53
Zambia	70,264	24	9	1.1	63.79
Ethiopia	68,026	10	7	2.6	49.89
Tanzania	58,820	22	8	1.6	48.14
Brazil	55,239	3	30	11.5	302.75
Chad	53,122	31	12	1.0	66.06
United States	49,679	5	21	7.3	141.98
Mozambique	44,353	25	10	1.7	43.12
Canada	35,429	19	46	2.9	616.91
Ukraine	35,133	57	26	0.4	159.70
Kazakhstan	31,858	14	11	4.8	39.02
Cameroon	29,643	30	18	1.9	59.19
Argentina	26,312	8	16	7.5	47.48
South Africa	24,313	21	13	4.0	33.00
Uganda	22,115	35	24	1.9	70.52

products. The spatial distribution of the areas burnt is approximately the same, but their extent is lower in the GLOBSCAR products, with a more scattered distribution.

3.2.2. Seasonal Distribution of the Burning

[56] The African continent presents two clear burning seasons, with most of the burning taking place over sub-Saharan northern Africa during the December–February perio, while the southern Africa burning lasts from June to September. Burning in north Africa countries amounts to less than 0.5% of the overall burning for that continent and is therefore not discussed further in this paper.

[57] The general spatiotemporal pattern in southern Africa [*Cahoon et al.*, 1992] is of fire starting in May in the northwest part and sweeping southeast to reach the east coast of South Africa in September/October period. According to GLOBSCAR, the peak of burning occurs over the June–July period, owing to the important contribution of the more northerly countries of southern Africa such as the Democratic Republic of Congo (DRC), Angola, and northern Zambia. Local experts confirm this trend (J. M. C. Pereira, private communication, 2003; P. Frost, private communication, 2003; R. J. Scholes, private communication, 2003; H. Eva, private communication, 2003). These results are also in line with remote sensing products such as GBA-2000 or the active fires detected by DMSP [*Cahoon et al.*, 1992]. The most important ecosystem for biomass burning in the region is the wetter Miombo, located in those countries (http://miombo.gecp.virginia.edu/). However, precise figures on the spatial and temporal distribution of fire in miombo are not available because of the limited field reporting in those countries, especially compared to much better monitored countries such as South Africa or Mozambique. This explains why other publications, focused on the SAFARI experiment and therefore on areas more easily monitored, which are more toward the south, tend to identify the peak of burning around the July–September period [*Justice et al.*, 1996].

[58] On average, the GLOBSCAR, GBA-2000, and WFA products display similar trends on the African continent. The more noticeable differences between the three products are listed below.

[59] In South Africa the area burned is a factor of 3 greater for GBA-2000 than for GLOBSCAR. The validation of the GLOBSCAR products in this country [*Fierens*, 2002] showed regular under-detection problems.

[60] In Namibia, GLOBSCAR detects only 7% of the burnt areas detected by GBA-2000. This seems to be partially a case of under-detection since some active fires are detected by the WFA without any corresponding burnt areas in GLOBSCAR. No obvious explanation could be found for this under-detection, especially since it occurs in several different land cover types, including savannas and open shrubland, where successful detections are performed in other countries.

[61] Some fire activity takes place in southern Africa and over Madagascar over the period January to March according to GLOBSCAR and also to the ATSR-2 WFA, but there is no detection in the GBA-2000 products. This is explained by the fact that the GBA-2000 regional algorithm is not run over these areas during that period, which is considered out of the burning season. For example, the large fire that took place near Cape Town in January 2000 with over 8000 ha burnt [*Calvin and Wettlaufer*, 2000] (see the Global Fire Monitoring Center Web site at http://www.fire.uni-freiburg.de) is detected by GLOBSCAR but absent from the GBA-2000 product.

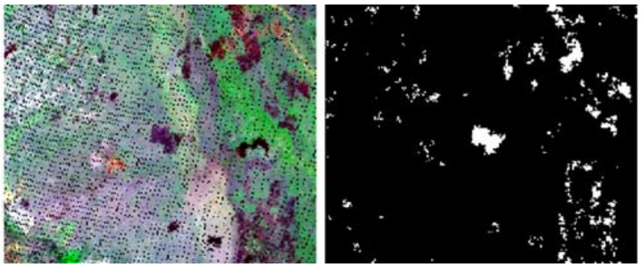

Figure 7. Example of good detection over Mozambique in late August 2000. (left) Some active fires can be seen in the ATSR-2 GBT image. (right) The areas detected as burnt are shown in white.

3.2.3. Specific Results

[62] An example of local GLOBSCAR results obtained over a specific region is shown in Figure 7 (in this case, Mozambique in late August) over cropland and savanna areas. The results are satisfactory, with most of the burnt perimeters being picked up by both algorithms and therefore by the final product. The more recent burnt areas are those best detected.

3.3. North and Central America

[63] GLOBSCAR results indicate a total of 11.1 Mha burnt over the American continent, mostly split between the United States, Canada, and Mexico. Thirty percent of these burnt areas are situated in forested areas. The national statistics extracted from the GLOBSCAR results are not truly representative of the results obtained and hide two contrasting problematic issues: some isolated false detections in arid mountainous areas, possibly owing to darker rocks or shadow effects, and scattered detection of the larger burnt areas, mostly owing to E1 under-detection.

[64] One unusual characteristic of the GLOBSCAR results is the burning in May–June over nonforested areas in the northern part of the United States. The areas are not detected as affected by fires according to either WFA or GBA-2000 results. One possibility is that these detections correspond partly to agricultural prescribed burning, but there seems to be a number of false detections that could be due to some land cover type confusion. Also, according to H. Eva (private communication, 2002), some of the detections in the south of the Chaco, New Mexico, during the winter period (November–December) may correspond to local flooding. The burning in Canada is equally split between forested and nonforested areas, with 1.5 million hectares burnt over forested areas out of the overall 3.5 million hectares burnt annually. For comparison, national statistics reports a total of 664,734 ha burnt in 2000 over forested areas (from the Canadian National Forestry Database Program, available at http://nfdp.ccfm.org). The GLOBSCAR figures over forests are therefore twice the amount of national reports. In addition, the peak of burning occurs in June instead of the traditional late summer peak in August, and the ranking of the provinces affected by fires by GLOBSCAR contrasts with the national statistics. In particular, the results over Alberta are problematic, with

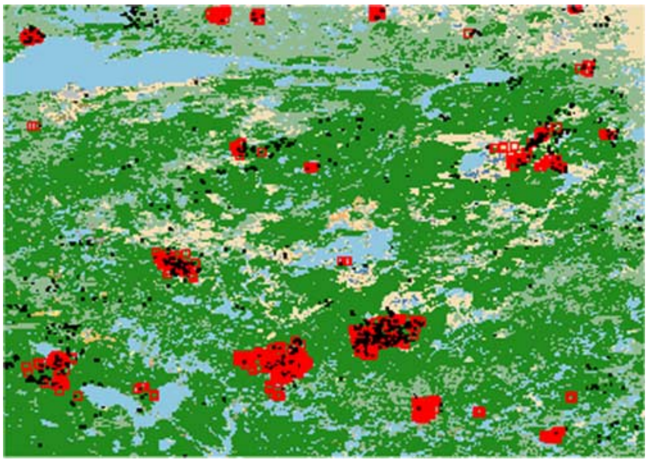

Figure 8. Example of detection of older burnt areas in Canada. Active fires (WFA) from summer 1998 are overlaid with GLOBSCAR results of June 2000 (in black). The area displayed is in the northern part of Canada, around 107° west/57° north.

GLOBSCAR detecting 17 times more forested areas as burnt than official statistics. The overall GLOBSCAR results are six times larger over Canada than that reported in the GBA-2000 products. While the authors of the GBA-2000 products acknowledge under-detection problems over Canada (see http://www.gvm.sai.jrc.it/fire/gba2000/index.htm), the GBA-2000 results [*Fraser et al.*, 2003] seem, however, on the whole more in line with the expected features of burning in Canada: the peak of burning occurs in August, and the provinces affected by fires are ranked in approximately the same order as the national statistics. Further analysis of the results has shown that a number of these detections correspond to older burn scars. An example of such detection is shown in Figure 8. This problem is further analyzed in the discussion.

3.4. South America

[65] There are two peaks of burning in South America, one in January (Colombia, Venezuela, Argentina) and one in August–September (Brazil, Argentina, Bolivia). Brazil accounts for 41% of the total burning followed by Argentina (19%) and Colombia (11%). Only a small proportion of those burnt areas (8% on average) are situated over forested areas. This is the case for Brazil, with only 433,000 ha of forests affected by fires, out of the total 5.5 million hectares burnt.

[66] According to H. Eva (private communication, 2002), the GLOBSCAR results seem to generally equate with what might be expected in the area. One caveat noted is the presence of a large number of detected burnt areas in the Peruvian Andes. These seem to follow the dry valley bottoms, which often have scrub that resembles burnt surfaces. These are likely commission errors.

[67] Some of the detections in the Llanos de Mojos, Bolivia, during winter (November–December) may correspond to flooding. However, in the Northern Hemisphere (llanos of Colombia and Venezuela), there appears to be no such problem. This might be explained by a slight shift in the burning season in 2000.

[68] Over Brazil, GLOBSCAR detects many more areas as burnt than GBA-2000, by a factor if 3 with around 55,000 km^2 burnt for GLOBSCAR against 18,250 km^2 for GBA-2000. The spatial distribution is comparable to WFA. Under-detection by GLOBSCAR is observed in this country (as shown in Figure 9), but it seems that under-detection by GBA-2000 is even more severe. Under-detection in the forested areas is mainly caused by the under-detection of the E1 algorithm (shown in Figure 9 and discussed later on in this paper). An additional potential cause of under-detection is the average small size of burnt areas in this type of land cover, below the detection rate of the instrument data. Cloud coverage seems to be less problematic in the area during the July–September burning period compared to other tropical areas such as Indonesia for example (see Figure 10 for ATSR cloud-free observations in July).

3.5. Australia

[69] The total burning recorded amounts to 18 Mha. This is much lower than the figure of 71.2 million hectares of so-called ‘‘fire affected area’’ reported by *Food and Agriculture Organization* [2001] on the basis of remote sensing monitoring performed by the Western Australian Department of Land Administration (DOLA). The core of the Australian burning season extends from June to September with a peak in September. According to the GLOBSCAR results, the Northern Territory, Western Australia, and Queensland account for 95% of the total burning.

[70] The validation campaign showed regular occurrences of under-detection by GLOBSCAR, in particular, over semiarid regions. This indication of under-detection is confirmed by the number of active fires present in the WFA and missed out in GLOBSCAR. The GLOBSCAR

Figure 9. Under-detection by E1 in the Brazilian forest in July. (left) The burnt areas can be seen on the ATSR image. (center) They are detected by the K1 algorithm but missed out by (right) the E1 algorithm.

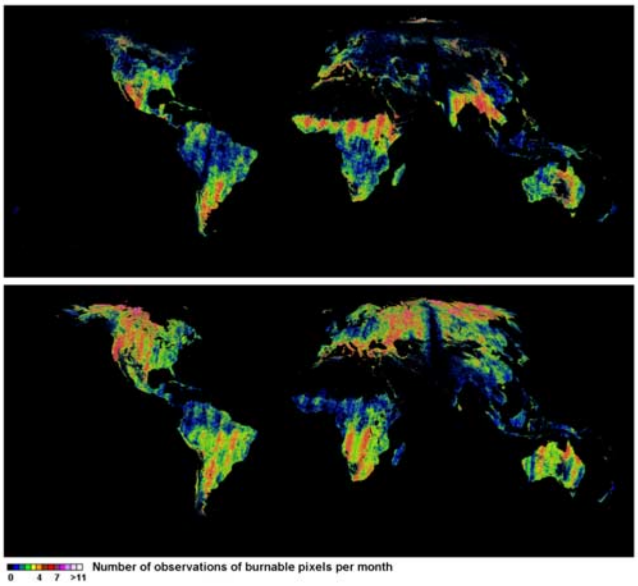

Figure 10. Examples of the number of cloud-free observations available per month using ATSR-2 daytime data, for burnable pixels only. Nonburnable regions (according to IGBP classification) are directly eliminated and therefore shown in black (e.g., water pixels or Sahara region). The highest revisit frequency is at the high latitudes in the summer months. The data gap in Siberia can be seen on the July 2000 picture. The frequent cloud coverage over Indonesia is also clearly shown in these examples.

results are also a factor of three lower compared to GBA-2000 results. The areas presenting those under-detection problems are areas of sparse vegetation, mostly open shrubland. In dry regions of Australia the E1 algorithm is mainly responsible for the large level of under-detection in the GLOBSCAR products.

3.6. Asia

[71] With 21.2 million hectares burning annually, the Asian continent accounts for 11% of the total burning. Fire activity takes place in the first quarter for southeast Asia and a large peak in June–July for Asian Russia, Mongolia, and Kazakhstan, who together contribute to 66% of the total burning figures of this continent. Twenty-five percent of the areas affected by fires are in forested zones. There were no validation data available for the project in the area, but general comments can be made on the results obtained. The spatial distribution of the areas affected by fires according to GLOBSCAR is generally consistent with the other remote sensing products available, and the seasonality of the burning is according to expectations. One problematic area is India, which shows some strong under-detection. In this country the GLOBSCAR results represent only 16% of the GBA-2000 results. This can be explained mostly by a data gap in the central western part of the country owing to the satellite descoping, and by the dense cloud presence, particularly around June.

[72] Another difficult area is Indonesia, where most of the burning is missed out by GLOBSCAR (and other burnt area products such as GBA-2000) owing to the systematic presence of clouds, especially during the burning period, which reduces dramatically the number of clear ground observations available.

[73] Looking at the differences between GLOBSCAR and GBA-2000 over Asia, one can notice that there are more detections by GBA-2000 in countries such as Kazakhstan or Mongolia over grassland, cropland, and natural vegetation land cover types according to IGBP classification. These are likely cases of under-detection in the GLOBSCAR products since some active fires are often recorded in the WFA over the areas of discrepancies. This might be due to a variable severity in the burning, or to an algorithm threshold problem for K1 since in other occasions the areas detected by the two burnt area products over the same region and ecosystem are in good agreement.

[74] Comparable results are obtained with both products in countries such as Myanmar or Cambodia. Fifty percent (respectively 30%) of the burning in those countries in situated in forested areas.

[75] Finally, in Thailand, GLOBSCAR reports three times as many burnt areas as GBA-2000. This corresponds to detections over forested areas, and also croplands, in the central and northern part of the countries. Active fires are recorded in the WFA corresponding to those burnt areas, so here this might be a case of under-detection in the GBA-2000 products instead.

3.7. Europe

[76] The total burning recorded over Europe (European Russia excluded) amounts to 5.75 million hectares, with 2.1 million hectares over forested areas. National statistics reported by *Food and Agriculture Organization/United Nations Economic Committee for Europe* (*FAO/UNECE*) [2001] indicate a total of 880,370 ha burnt over the same region in 2000 over forest, wooded land, and other land areas according to the FAO classification. This classification does not map directly to the IGBP classification. However, since the IGBP forest classification is more conservative, it indicates that larger areas are detected as burnt in the GLOBSCAR products compared to national reports.

[77] The biomass burning in western and southern Europe amounts to 765,000 ha, among which 99,700 ha are over forested areas. The total burning figure is in line with the average of 600,000 ha burnt annually over forest and other land areas in Mediterranean countries according to IFFN statistics [*International Forest Fire News* (*IFFN*), 2000]. On the whole, good results are obtained over several southern Europe countries according to local experts. This is true of Portugal and Greece, for example. A local analysis was conducted in the case of the August 2000 fires of Corsica, France. GLOBSCAR detects the two major fires in the central part of the island; however, the total area reported as burnt is less than the official reports, which indicates under-detection by GLOBSCAR, mostly owing to a lack of an appropriate region-growing scheme. This was confirmed upon inspection of a Landsat/TM image of the area dated from late August 2000.

[78] Northern and eastern Europe burning totals up to approximately 5 million hectares (excluding European Russia), out of which only 109,500 ha are attributable to IGBP forested areas. A large spring burning is recorded over eastern European countries, in particular, Ukraine (5.8%

of the territory affected by fires according to GLOBSCAR). This burning affects pixels that are classified mostly as croplands (classes 12 and 14 of IGBP land cover classification). In those areas, there is a large difference between the WFA and both burnt area products throughout the April to June period: the large amount of burnt area recorded by both GLOBSCAR and GBA-2000 does not correspond to active fires in the WFA. Further investigation indicated the presence of smoke plumes in high-resolution imagery (Landsat TM quick looks) during that period, and the detection of some active fires by the MODIS fire product during the same period of the year in 2001 (the product is not available for spring 2000). One suggested interpretation is that the areas detected as burnt correspond to prescribed burning over cultivated areas occurring mostly during daytime. This would explain the nondetection by the WFA (nighttime product). National statistics do not report on agricultural and prescribed burning; therefore there is no statistical source of information on the amount of areas affected.

3.8. Russian Federation

[79] According to GLOBSCAR, a total of 20 Mha burnt in 2000 in the Russian Federation distributed between 10.2 Mha burnt over European Russia and 9.7 Mha over Asian Russia. In the European part of the territory, only 440,000 ha correspond to forest fires, against 3.57 Mha for the Asian part. For indication, national reports indicate a yearly figure of 1.9 Mha for the Russia Federation in 2000 [*FAO*/*UNECE*, 2001] over forest, other wooded land, and other land territories. A direct comparison is made difficult since national statistics do not map directly against the IGBP classification. However, generally speaking, both the GLOBSCAR figures and GBA-2000 results are significantly larger than national reports. Most of the burning occurs in late spring followed by the traditional summer burning (July–August). The burning is equally split between Asian and European Russia. For the Asian part it is concentrated in the Chitinskaya Oblast (May) and Republik Sakha (Yakutiya, June–July) regions. For the European part the regions with highest burning figures are in decreasing order Rostovskaya Oblast (May, August), Krasnoyarsky Kray (April, August), and Voronezhskaya Oblast and Amurskaya Oblast (May).

[80] There are cases of likely false detections over open shrubland areas in the northern part of Siberia. This detection may be due to the predominance of low solar angles. Masking out all burnt areas detected over open shrublands solved a similar problem encountered in the GBA-2000 results.

4. Discussion

[81] While the GLOBSCAR products can be seen as instrumental toward a better understanding of the quantification and seasonal distribution of the biomass burning at larger scales, the review of the regional performance of the products has raised a number of issues, some of which relate to the algorithms performance and limitations, while others are linked to the remote sensing nature of the products.

4.1. Algorithm Issues

[82] The first important point regarding GLOBSCAR algorithms is that single thresholds were selected when applying the algorithms at global scale. One reason for this is the limited accuracy of any land cover information available at the time of the project (DISCOVER project based on AVHRR 1992–1993 data; *Loveland et al.* [2000]), which makes unreliable any land cover related threshold approach. The choice of single thresholds can induce significant commission errors by the individual algorithms when they are applied globally. However, in most cases, these commission errors do not overlap owing to the very different nature of the algorithms. In order to minimize commission errors in the final results, the option to use both algorithms together (E1 and K1) was retained as the best available option for the final products: only pixels detected by both algorithms were retained.

[83] As a result, commission errors are only rarely observed and occur mostly on isolated pixels. The only notable source of commission errors is the detection of older burn scars, which has been clearly observed in the mixed and evergreen needleleaf forests of Canada (see Figure 8), and which is also probably occurring in similar ecosystems in Russia. In principle, the use of a temporal mask to make the product incremental should solve this problem, but here the cloud and snow cover are such that in the first month used as reference for the project (December 1999), there is neither observation nor detection of these burnt areas. In fact, these are detected for the first time in May–June, when the conditions of observation allow it. This explains the peak of detections in June for Canada, when accumulated older burn scars are detected. A possible solution would be to ignore detections occurring before July in those areas: this would mean missing out on the few fires that do occur during the May–June period but would improve the overall performance of the GLOBSCAR products over that area. In the case of a multiple year product, one could also consider using September of the previous year as a basis for the incremental product for the first months of the burning season (May–June) rather than the preceding month, which has limited observation capability. The use of the Canadian Large Fire Database [*Stocks et al.*, 2002] could also be of interest, but would introduce a difference in the way boreal forests of Canada and Siberia are treated in the product since no similar database is available for Russia.

[84] Omission errors occur regularly and can be significant in some regions. Areas of important under-detection include, for example, the United States (open shrubland and grassland areas), Australia (open shrublands), Zimbabwe (cropland), and Brazil (broadleaf evergreen forests). Options to get around these under-detection problems include the use of modulated thresholds for the algorithms, which would require an improved source of land cover information. The new GLC2000 product (E. Bartholomé and A. S. Belward, GLC2000: A new approach to global land cover mapping from Earth observation data, submitted to *International Journal of Remote Sensing*, 2004) could represent an appropriate such source of information. Another possibility would be to combine in an appropriate manner the GLOBSCAR results with other burnt area approaches such as GBA-2000.

4.1.1. K1 Algorithm

[85] K1 algorithm performance depends on burnt areas exhibiting a large separability in the NIR-TIR feature space.

This is not always the case, and the capability to discriminate between burnt and nonburnt areas becomes then very restricted. The mixing of burnt and nonburnt pixels in the NIR-TIR space can result in either commission or omission errors, which are difficult to avoid. Another potential source of commission errors by K1 is the case of dark bare soils. If combined with vegetation within the processing window, these surfaces can present lower NIR and higher TIR characteristics with respect to the vegetation and be therefore wrongly detected as burnt areas. It should be noted that commission errors are largely eliminated from the final products by the use of the E1 algorithm as a check on the NIR and TIR absolute values, while omissions remain as omissions in the final products, even if detected by E1. One way to reduce those omissions would be to lower further the K1 threshold, but this would result in a substantial increase of commission errors in other regions, which would not be necessarily eliminated when using an additional algorithm. Another option would be to set up land cover related thresholds for K1, which would require in turn both a reliable land cover information and very accurate georeferencing of the pixels.

4.1.2. E1 Algorithm

[86] The main limitation encountered with this algorithm resides in the commission errors owing to confusion with water pixels. Problematic areas are therefore temporarily flooded zones since most other water areas are masked out from burnt area detection early in the processing by using land cover classification information. Such an overdetection problem was reported during the validation of the products, for example, in the Okavango delta [*Fierens*, 2002]. Several of the algorithms developed under the GBA-2000 initiative [*Tansey et al.*, 2002] present similar commission error problems, which were resolved by a variety of postprocessing techniques, and by not processing the data out of the burning season. One possible solution to avoid these false detections by E1 would be to introduce a minimum threshold value on the NIR.

[87] The E1 algorithm also exhibits significant under-detection problems in some particular ecosystems such as the dry regions of central Australia or tropical forests in South America. An example of such under-detection can be seen in Figure 9 over Brazil. K1 detects the burns well, but under-detection by E1 results in under-detection for the overall product. Improving the results in that area would require identifying which of the E1 tests is too stringent and needs relaxing for this particular situation.

4.1.3. Region Growing

[88] One other reason for omission in the final products is the lack of any region-growing mechanism during the processing. The original algorithms were developed with the objective of keeping the processing load to an acceptable level considering the amount of data to be processed within a limited period, but this results in patchy patterns in the final products, with no mechanism in place to "fill the holes." In order to improve the results, some postprocessing steps should be added to the processing system to check the values of pixels surrounding high confidence burnt pixels through a region-growing methodology as used in GBA-2000.

[89] Despite these limitations, the use of the same systematic algorithm combination globally has some definite advantages. It makes the overall processing system quite simple and produces a homogeneous product, with clear characteristics. That way, problems and limitations are more clearly identified and consequently addressed. In addition, the approach guarantees that similar land cover types are treated equally around the globe, which is very important for the modeling of the associated emissions.

4.2. Product Issues

4.2.1. Cloud Coverage and Revisit Frequency

[90] The limited revisiting frequency (only up to 10/month at the equator) means that in some very cloudy areas (e.g., Indonesia or Brazil) the number of observations available for a given pixel can be down to 0–1 per month. This can result in large under-detection of the burnt surfaces over these areas. Instead, an active fire product such as the WFA does not necessarily encounter the same limitations: the nighttime fire signature in the 3.7 micron gets usually sufficiently strong to allow detection, even in cloudy conditions.

[91] Figure 10 illustrates this limitation by showing some examples of monthly available ATSR cloud-free observations. It is particularly critical in those areas where the burning potentially results in dense smoke and consequently no clear ground observations available. Some means of "seeing past the cloud" is required, especially in the equatorial regions. This could be achieved with more frequent observation, the use of multiple sensors, alternative sensors such as radar that are not affected by cloud, or by knowledge of the statistics of the under-detection to allow for an a posteriori adjustment.

4.2.2. ATSR-2 Data Gap

[92] The ATSR-2 land data set exhibits a regular data gap, mostly in Russia and India (north-south course), and in small places of Australia. This is due to the ERS-2 satellite-descoping scenario, where the telemetry available for the ATSR-2 data was sometimes constrained by the requirements of other instruments. Since the ATSR-2 instrument was designed for ocean applications, the descoping was therefore assigned over land. The data gap can be clearly seen on Figure 10; in this case, during the month of July. It causes under-detection of the burnt areas in those regions. Since the data are not available, there is no algorithm solution for this problem. Instead, the solution could be the use of multiple sensors to achieve full global coverage. It should be noted that the follow-on system to ATSR-2, AATSR, does not suffer from the same problems since the data telemetry for the ENVISAT satellite ensures continuous data reception.

4.2.3. Small Fires

[93] Small-sized fires below 1 km^2, which are an important emission contributor and might alter the burn seasonality for the affected regions, are not accounted for in the GLOBSCAR products owing to the instrument data resolution. Small hot fires can present a strong enough signature in the MIR that their contribution to the integrated MIR value over the 1 km cell is sufficient for detection. In the case of the ATSR-2 WFA, for example, the detection capabilities of the algorithm are estimated at 0.1 ha at 600 K to 0.01 ha at 800 K for a background temperature of 300 K. Instead, the spectral contrast of burnt areas is much lower than for active fires. A large proportion of the

1 km cell must therefore be burnt to allow for the detection by the algorithm. Accounting for these fires would require finer-resolution instruments, or a synergetic use of active fire and burnt area products, whereby the presence of an active fire would relax the rules established for burnt area detection. The WFA would probably not be appropriate for such use since it is nighttime and therefore tends to miss out small fires that usually get extinguished within the same day of ignition.

4.2.4. Under-Storey Fires

[94] Under-storey peat fires cannot be detected by satellites, first because of their low temperature and second because the surface albedo does not necessarily change. These kinds of fires represent an important contribution to trace gas emissions, e.g., in Russia and Indonesia. An alternative solution should be sought to account for these fires. It may lie in the use of combined field and remote sensing observations.

4.2.5. Agricultural Fires

[95] Agricultural fires usually take place during daytime and do not last long in time. For these reasons, they tend to be better detected by burnt area products than active fire data products. This is particularly true of the WFA, which is a nighttime product. However, in order to get detected by low spatial resolution sensors, the areas burnt need to be sufficiently extended in space.

4.3. Implications for the Use of the Product

[96] On the basis of the findings of this analysis of the GLOBSCAR products, a summary of implications for the user community is proposed here, with particular emphasis on their use as input data for modeling activities.

4.3.1. Omission Errors

[97] Compared to active fire data sets such as the ATSR-2 WFA, the GLOBSCAR products represent a definite improvement toward a better quantification of the areas burnt at global scale. However, a significant level of omission exists and needs to be accounted for in modeling activities. The main sources of omission in the GLOBSCAR products together with the areas affected can be listed as follows:

[98] 1. No region-growing mechanism (global, all vegetation types).

[99] 2. Nonexistent input data due to the satellite descoping scenario (parts of central Russia and northern India, visible on Figure 10, all vegetation types affected).

[100] 3. High cloud coverage during the burning season (mostly Indonesia, Central America, and Brazil to a lower extent, all vegetation types affected).

[101] 4. Under-detection by E1 algorithm (in dry regions of central Australia, mainly over open shrublands, in the evergreen broadleaf forests of South America).

4.3.2. Commission Errors

[102] The GLOBSCAR products present a limited number of commission errors, which is an important asset for modeling applications. However, some areas remain where there are indications of commission errors:

[103] 1. Possible false detections due to the predominance of low solar angles over some open shrubland areas in the northern part of Siberia; so far the only solution identified to solve that problem is to apply a land cover related mask and rule out open shrubland burnt areas at the high latitudes, as done in the GBA-2000 product.

[104] 2. Detection of older burnt areas exhibiting long-term low NIR and high TIR signatures (boreal forests of Canada and possibly Russia); this could be solved by using as reference not only the preceding month but also September of the previous year when deriving the incremental product.

[105] Finally, the spring detection of areas burnt in agricultural zones of central Europe and northern America may include false detections in some places caused by seasonal cultivation practice (ploughing, dark soils surrounded by cultivated areas), although this has not been confirmed so far.

4.3.3. GLOBSCAR and WFA

[106] While active fire products provide more precise timing information on the fires, which can be very useful for short-term emissions modeling, the large number of missed fires in active fire products such as the WFA (nighttime only, 3-day revisit) means that they are not truly representative of the extent of burning. Intercomparison between the WFA and GLOBSCAR results at large scale has shown that these represent two complementary sources of information on fire events and should therefore be used in a synergetic manner.

4.3.4. GLOBSCAR and GBA-2000

[107] The differences observed between two independently produced burnt area products, GLOBSCAR and GBA-2000, illustrate the difficulty in providing a single reliable global burnt area product using one sensor and one approach only. There is therefore a need for consolidation of the results obtained from the individual products by exploiting their respective strengths and suppressing their respective weaknesses. Increasing the number of ground observations available for a given area is also necessary for regions frequently covered by clouds. This could be achieved through a multisensor product approach.

4.3.5. Land Cover Information

[108] In both GBA-2000 and GLOBSCAR projects, land cover products were required either for masking purposes or to control algorithms. The lack of contemporary sources of land cover can be identified as having an impact on the product generation. Such contemporary information would make the tuning of the algorithms, depending on the type of land cover present, a possibility. In addition, the verification of the products is dependent on comparison with national and regional statistics, which are based on quite different notions of land cover. Therefore it is suggested that the availability of a reliable and contemporary source of land cover information, which is linkable to land cover definitions used for national and regional reporting, would improve both the overall results and their interpretability.

4.3.6. Application

[109] The GLOBSCAR results have been used to help produce an inventory of the emitted trace gases and the main aerosols emitted by biomass burning for the year 2000 for a global chemistry transport model (CTM). Details on this application can be found in the work of *Hoelzemann et al.* [2004].

5. Conclusions and Perspectives

[110] The GLOBSCAR project and the resulting products have been presented. Their strengths and weaknesses have

been reviewed and discussed and suggestions for improvement have been made.

[111] Despite the technical difficulties encountered, interesting results have been obtained, and the potential of remote sensing products has been demonstrated, particularly in areas for which field reporting is problematic either for geographical or political reasons (e.g., over some of the southern Africa countries). Building upon the experience gained within the GLOBSCAR project, several additional needs have been identified and are now briefly reviewed.

5.1. Consolidation of Existing Products

[112] Further analysis of the GLOBSCAR products performance would be of interest for the problematic areas identified in this paper. Examples of problems include the likely commission errors observed in the United States or the possible shadow detection in the Andes region of Chile. Such analysis would require local field knowledge and good quality contemporary land cover information. The use of the GLC2000 product combined with local expertise could be a viable way to address these issues. In addition, efforts should be made toward harmonizing the different existing burnt area products derived so far, ideally through a multisensor approach.

5.2. Multiyear Products

[113] A burnt area product available over 1 year only is of limited interest to the user community in view of the high interannual variability of fire events globally. In this respect, GLOBSCAR or GBA-2000 products can only be seen as demonstrator products. In order to actually deliver products for operational use, it is therefore essential to produce multiyear information. This is particularly needed for atmospheric chemistry modeling applications.

5.3. Information on Fuel Load

[114] In addition to providing information on the extent of the burning, there is a clear need for the provision of adequate information on the potentially burnable vegetation, i.e., the available fuel load. This requires contemporaneous monitoring of vegetation amount and state through estimation of biomass or associated variables such as the leaf area index (LAI).

5.4. GLOBCARBON Project

[115] The new ESA project GLOBCARBON [*Plummer et al.*, 2004] will aim at tackling all three issues raised above. The objectives of this project are to develop and demonstrate a service for the production of multiyear level 3 global land products to be used for global carbon modeling. The burnt area product is the priority product of the system and builds upon the experience gained within both the GLOBSCAR and GBA-2000 projects. The service will also generate global estimates of LAI, a fraction of photosynthetically absorbed active radiation and vegetation growth cycle. The processing system is based on a multisensor approach to avoid dependence on a single instrument or platform, to make observations more frequent, and to build confidence in the estimates.

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