An evaluation of the global 1-km AVHRR land dataset

P. M. TEILLET
Canada Centre for Remote Sensing, 588 Booth Street, Ottawa, Ontario, K1A 0Y7, Canada; e-mail: phil.teillet@ccrs.nrcan.gc.ca

N. EL SALEOUS, M. C. HANSEN
Department of Geography, Lefrak Hall, University of Maryland, College Park, Maryland, USA

J. C. EIDENSHINK
EROS Data Center, Sioux Falls, South Dakota, USA

C. O. JUSTICE
Global Environmental Change Program, Department of Environmental Science, Clark Hall, University of Virginia, Charlottesville, Virginia, USA

and J. R. G. TOWNSHEND
Department of Geography and Institute for Advanced Computing Studies, Lefrak Hall, University of Maryland, College Park, Maryland, USA

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Abstract. This paper summarizes the steps taken in the generation of the global 1-km AVHRR land dataset, and it documents an evaluation of the data product with respect to the original specifications and its usefulness in research and applications to date. The evaluation addresses data characterization, processing, compositing and handling issues. Examples of the main scientific outputs are presented and options for improved processing are outlined and prioritized. The dataset has made a significant contribution, and a strong recommendation is made for its reprocessing and continuation to produce a long-term record for global change research.

1. Introduction

This paper documents the generation and evaluation of the global 1-km AVHRR land dataset (hereafter referred to as the G1KA dataset) based on imagery from the Advanced Very High Resolution Radiometers (AVHRRs) on board the series of US National Oceanic and Atmospheric Administration (NOAA) satellites. The G1KA dataset was initiated by the International Geosphere–Biosphere Programme (IGBP) and has been implemented through the collaboration of many agencies, and by the US Geological Survey (USGS) EROS Data Center (EDC) in particular. After reviewing the rationale for the dataset and summarizing its characteristics and current status, the paper outlines an evaluation of the product, mainly with respect to the original specifications but also with respect to its usefulness in research and applications. The paper also highlights examples of the most significant science contributions (global land-cover classification and global fire products) and outlines various options for reprocessing and continuation of the data record.

As implemented, this unique product is highly compliant with respect to IGBP requirements overall and has been ordered by tens of thousands of users. The dataset is a worthwhile accomplishment in its own right but also because of the groundwork it lays for continued generation of a global land data record at the 1-km scale using current and future Earth observation sensors. While quality assessment of the product indicates some shortcomings (as is inevitably the case with any experimental product), several of the problems identified have already been corrected by EDC. To overcome other deficiencies requires more advanced processing. Overall, the G1KA dataset should be considered an achievement with a significant scientific impact.

2. Earth observation data product evaluation

It is important to make the distinction between evaluation and validation. An evaluation is a determination or appraisal of worth or value, whereas validation is a confirmation by independent facts or authority. In the Earth-observation context, the internationally accepted definition of validation is the process of assessing by independent means the quality of the data products derived from the system outputs (Belward 1997). In either case, the assessment must be carried out with respect to some criterion, standard, model, requirement or specification, and it will nominally involve a methodology as well as metrics and/or reference data.

The evaluation of Earth observation data products could be approached in several possible ways, including internal project evaluation, the unfunded collection of user experiences and/or synthesis by independent volunteer experts or a funded independent evaluation program. There have been several programs to evaluate the performance of Earth observation sensor systems post-launch and to evaluate the quality of the image data acquired by the sensors, but fewer higher-level product validation programs have been carried out because of the challenges involved. In conjunction with the Landsat-4 and Landsat-5 missions, the US National Aeronautics and Space Administration (NASA) funded some 40 investigation teams in the Landsat Image Data Quality Assessment (LIDQA) program, where the emphasis was primarily on verification and characterization of the performance of the Thematic Mapper (TM) sensor and, to a considerably lesser extent, on applications (Markham and Barker 1985, Barker 1985, Salomonson 1984, Barker 1984). Both the Système pour l'Observation de la Terre (SPOT) and the European Remote Sensing (ERS) satellite programs included early assessment components, and the current Earth Observing System (EOS) and Envisat programs have the most extensive validation programs ever undertaken.

However, co-ordinated evaluations of global land datasets in general, and AVHRR datasets in particular, have seldom, if ever, been undertaken, even though AVHRR data are probably some of the most widely used remote sensing measurements in the civilian sector. Although systematic testing and evaluation are key steps in the life-cycle of a major product, the nature of the G1KA activity has been such that significant resources were made available for data archiving, processing and distribution only and not for data product evaluation or for applications development. Hence, the methodology for an evaluation of the G1KA dataset has necessarily been less rigorous than desired, limited mainly to assessments by volunteer experts and inputs from a modest number of users in the community. The evaluation criteria were twofold: (1) a comparison of implemented data product characteristics with respect to the original specifications and (2) a review of user inputs with respect to the G1KA dataset's usefulness in research and applications. The evaluation also identifies and documents characteristics of the dataset affecting data usage and provides input to decisions on future processing activities.

3. Rationale for the dataset

3.1. *Scientific requirements*

Research into global change has risen significantly in scientific priority for some time. Examples of the need for information on land attributes include investigations of

- climate based on need for variables describing surface roughness, albedo, latent and sensible heat fluxes;
- biogeochemical cycles and atmospheric chemistry, through such attributes as land-cover conversion and modification, as well as the rate, distribution and type of biomass burning events; and
- water–energy–vegetation studies for which information on soil moisture, land transformations and evapotranspiration is required.

A decade ago, there was a dearth of global information on these attributes of the land surface. The existing global datasets were largely derived from the piecemeal collation of diverse datasets, which gave rise to major problems of spatial and categorical consistency. Because of such difficulties with traditional information sources, remote sensing from space became increasingly regarded as an essential source of data, especially for those attributes requiring global or regional coverage and regular monitoring or updates. Information extraction from remotely sensed data for land applications can be carried out through two basic approaches. In the first, land-cover characterization through classification is initially carried out and then values of biophysical variables are assigned to each of the classes. Alternatively, direct estimation of biophysical variables may be attempted through either statistical methods or explicit inversion techniques.

The United Nations Food and Agriculture Organisation (FAO) Forest Resources Assessment Project requires 1-km AVHRR data to map the extent of all the forestlands on the planet every 10 years, with emphasis on the tropical zones, for their global forest statistics mandate (FAO 1990). NOAA researchers also need a 1-km AVHRR dataset of the northern hemisphere to study the urban heat island effects on surface observations of temperature data (Gallo *et al.* 1993). The European Commission and the European Space Agency (ESA) have a joint requirement for global, near daily, long-term, consistent optical and thermal satellite data for tropical environments in support of the joint Tropical Ecosystem Environment Observations by Satellite project (Malingreau and Belward 1994). The NASA EOS Moderate Resolution Imaging Spectroradiometer (MODIS) land science team has concluded that a global land 1-km AVHRR dataset is crucial to the early implementation of algorithms for several land products for EOS (Running *et al.* 1994). Recognizing the needs for an improved land dataset, the Plenary of the international Committee on Earth Observation Satellites (CEOS) endorsed the compilation of such a dataset, which helped to facilitate international co-operation to ensure participation in and completion of the first version of the G1KA dataset.

One especially important program that has fostered international co-operation has been the IGBP, which is concerned with the biogeochemical aspects of the Earth system. The initial Core Projects of this program were defined approximately 10 years ago (IGBP 1990) and a wide range of research activities have been undertaken. Two requirements common to all IGBP projects are (1) quantitative models to analyse the numerous complex interactions and feedbacks that occur within the Earth system and (2) large datasets containing geographically (or spatially) referenced data to parameterize and validate these models. In the preparatory phase of the IGBP, it became apparent that many of the required datasets either did not exist or only existed in forms ill-suited to global-scale investigations. As a result of this situation, it was decided to set up the IGBP Data and Information System (DIS), whose basic role has been to ensure that datasets become available in a timely fashion and in a form appropriate for the fulfilment of IGBP scientific objectives (IGBP 1994). In fulfilling this role, the IGBP-DIS has not been directly involved in data processing and dataset production, but rather has taken a proactive role in co-ordinating international activities to ensure that the necessary datasets are produced and made available. It was proposed by the IGBP-DIS that a global dataset of the land surface be created from remotely sensed data from the operational NOAA AVHRR sensors to support a number of IGBP projects (Townshend 1992a). This dataset would have a spatial scale of 1 km and would be generated at least once every 10 days for the entire globe. At that time, the AVHRR was the only 1-km dataset available to the community.

3.2. *Types and uses of AVHRR data*

Although many types of remotely sensed data of the Earth's surface have been collected for several decades, data from the AVHRR sensors have been used most frequently for global land studies, among many other applications. This is because the spectral bands are reasonably well suited to the detection of key terrestrial attributes, especially those relating to vegetation. Most importantly, the AVHRR provides data with a high enough temporal frequency that global datasets can be compiled with substantially reduced cloud cover. Hence, regular monitoring of almost the entire global land surface becomes feasible. The AVHRR does have significant limitations, especially relating to radiometric calibration, but international efforts have been made to ameliorate this particular problem (Guenther *et al.* 1997).

Numerous studies involving the use of AVHRR data have demonstrated their value in the estimation of various attributes of vegetation cover, including leaf area index (LAI), green leaf biomass, net primary productivity (NPP) and photosynthetic capacity. Estimates of evapotranspiration have been made, as well as surface temperature and the spatial and temporal distributions of fires. The precision of these estimates can vary substantially, and there needs to be a continuing dialogue between members of IGBP Core Projects and remote sensing experts to ensure that derived products are adequate for the scientific needs of the IGBP and the international user community it represents.

Prior to the G1KA project, one of the biggest difficulties relating to the data from the AVHRR was their availability. Although the whole global land surface is sensed on a daily basis, global datasets at the basic observation resolution of 1.1 km (nadir) are not centrally archived owing to limitations of on-board tape recorders producing Local Area Coverage (LAC) data and ground reception facilities. However, sampled global data are acquired regularly through on-board processing to generate

Global Area Coverage (GAC) data, with a nominal scale of 4 km. Even these data have not traditionally been available in a form suitable for use at a global scale for land applications.

At the start of the G1KA data project, the availability of AVHRR data was limited to the following (Townshend 1994a).

(1) The Global Vegetation Index (GVI) dataset that is created regularly by NOAA with a spatial scale of 15–20 km. This dataset has been a most important spur to the use of global datasets, but it is known to have a number of significant limitations, and revisions have been made from time to time.
(2) A NASA data product from the Goddard Space Flight Center (GSFC) based on the GAC data product has been generated with a spatial scale of about 8 km, produced on a continent-by-continent basis. However, in the early 1990s, it had not been produced on a globally uniform basis.
(3) Local 1-km data archives of varying spatial extent and length of historical record were available, such as through the NOAA LAC archive and from various national and regional reception facilities acquiring High-Resolution Picture Transmission (HRPT) data. Areas for which datasets were most readily accessible included the North American continent (from EDC and the Canada Centre for Remote Sensing (CCRS)), Europe and north-west Africa (through the ESA and some European research groups).

Subsequently, the joint Pathfinder activity of NASA and NOAA led to a complete retrospective AVHRR GAC dataset from 1981 onwards at a spatial scale of 8 km and a frequency of once every 10 days. The Along-Track Scanning Radiometers (ATSRs) on board ERS-1 and ERS-2 have acquired data at a nadir spatial resolution of 1 km since 1991, although with a lower temporal frequency than the AVHRR. Launched in early 1998, SPOT-4 includes the Vegetation (VGT) sensor with a 1-km spatial resolution capability. In the near future, several new sensors with similar spatial resolutions will become available, including the US EOS MODIS, the European Envisat Medium Resolution Imaging Spectrometer (MERIS) and Advanced Along-Track Scanning Radiometer (AATSR), and the Japanese Advanced Earth Observation Satellite ADEOS-2 Global Imager (GLI). The AVHRR series will also continue with the operation of the NOAA-15 satellite, already in orbit to replace NOAA-12, and the launches of NOAA-L and NOAA-M in due course. This series of operational satellites will be followed approximately 10 years from now by the US National Polar Orbiting Environmental Satellite System (NPOESS).

A comprehensive review of the numerous AVHRR ground receiving stations showed that 1-km data from virtually the entire globe could, in principle, be acquired through a co-ordinated effort. The main gaps in coverage were in south-west Asia and northern Siberia. It was concluded that international co-ordination could ensure that data from ground stations regularly and reliably supplemented the LAC data required.

In February 1992, NASA, NOAA, IGBP, and the USGS hosted the first Global Land 1-km AVHRR HRPT Ground Station Operators Meeting in Pasadena, California. Agreements were negotiated with the various organizations to ensure smooth project implementation. On 1 April 1992, the data collection effort began with 23 receiving stations world-wide plus NOAA LAC recorders capturing, copying and transferring the 1-km data to EDC. NASA asked EDC to co-ordinate the gathering and management of such a dataset as part of its role as the EOS Land Processes Distributed Active Archive Center (DAAC). Funds were identified for data acquisition and archiving (raw level-1) and subsequently for the processing of 18 months of data from 1 April 1992 to 30 September 1993. The target was for global composite datasets generated from the collected data to be available within 6 months of completion of the initial 18 months of data collection. It was recognized that, in several of the preprocessing stages, procedures were not well established and that it was likely that improved products would have to be created in future. An important lesson learned from the GAC processing was that several reprocessings are required in the life of a dataset. Therefore, it was recommended that the data be archived in a form that would readily permit future improvements to be made.

4. Processing standards and product specifications

The G1KA dataset was defined by consensus by the IGBP-DIS Land Cover Working Group (LCWG), via specialist meetings to specify data processing approaches and algorithms, with a belief that community consensus was feasible and desirable. An alternative model would have been to solicit investigators through an Announcement of Opportunity (AO) process (such as for AVHRR Pathfinder 2), which would have been more scientifically progressive but less connected to the general community. The processing stages were initially identified by the IGBP-DIS LCWG in Paris in October 1990 and documented in IGBP Report No. 20 (Townshend 1992a). Further recommendations on the product specifications were agreed upon at an international meeting of experts at the University of Maryland in December 1991 and documented in IGBP-DIS Working Paper #3 (Townshend 1992b). The processing standards and product specifications are best summarized by Townshend *et al.* (1994) and Eidenshink and Faundeen (1994). The most comprehensive documentation on the G1KA dataset effort in general remains the *International Journal of Remote Sensing* special issue on global datasets for the land from the AVHRR (Townshend 1994b). In most respects, the implementation has been entirely consistent with the specifications and has even improved on them in some instances. Product characteristics non-compliant with the specifications are identified in the following material. It is worth noting that quality assurance (QA) and quality control were not mentioned in any significant way when the dataset was first considered.

4.1. *Radiometric calibration*

It has been known for some time that radiometric calibration coefficients for data collected from the AVHRR sensors, especially in spectral channels 1 and 2, have differed substantially from the pre-launch coefficients and that the latter should not be used (Teillet *et al.* 1990, Teillet and Holben 1994). It should be noted that radiometric calibration was not initially a programmatic requirement for the AVHRR sensors given their intended meteorological applications. Nevertheless, the usefulness of AVHRR data for more quantitative applications has grown constantly over the years, and the significant degradation in radiometric response over time became a problem worth addressing. As a result, a variety of methods have been investigated by the research community, and time-dependent calibration coefficients and/or parameterizations have become available (Che and Price 1992, Rao and Chen 1995, 1996, Vermote and Kaufman 1995). Strong recommendations were made by the IGBP-DIS LCWG (Townshend 1992a,b) and the international CEOS Working Group on Calibration and Validation (WGCV) that NOAA should take responsibility for the post-launch radiometric calibration of the AVHRR sensors, including the acquisition, evaluation and wide dissemination of the calibration updates. Since then, NOAA has made a good effort to make calibration coefficient updates available to the user community, although data acquisition campaigns to provide absolute radiometric calibration updates remain far too infrequent.

In order to provide consistent and timely calibration coefficients for the 18-month period, it was recommended that the processing of the global 1-km product should make use of coefficients based on the anchored desert method of Holben *et al.* (1990) and Kaufman and Holben (1993). As summarized in table 1, the actual time-dependent calibration coefficients used in the implementation were taken from Teillet and Holben (1994) for the NOAA-11 AVHRR and based on the method of Vermote and Kaufman (1995) for the NOAA-14 AVHRR.

4.2. *Atmospheric correction*

Given the state-of-the-art in 1992, it was decided that atmospheric correction for only Rayleigh molecular scattering and stratospheric ozone absorption would be implemented. The Rayleigh scattering correction was to be based on Teillet (1990a). Ozone absorption correction was to make use of climatological tables by month and latitude primarily (based on London *et al.* (1976) and Hilsenrath and Schlesinger

Table 1. Key implementation features of the G1KA dataset.

Radiometric calibration
• Time-dependent radiometric calibration coefficients for NOAA-11 AVHRR based on Teillet and Holben (1994)
• Time-dependent radiometric calibration coefficients for NOAA-14 AVHRR provided by Eric Vermote and Nazmi El Saleous, and based on Vermote and Kaufman (1995)
Atmospheric correction
• Corrections for Rayleigh scattering and ozone absorption only
• Rayleigh scattering correction based on Teillet (1990a)
• Ozone climatology provided by Eric Vermote
• Image correction implementation based on Teillet (1992b)
• Look-up tables generated using 6S radiative transfer code
• Terrain elevation data from GTOPO30
• Corrections applied to composite data, not daily observations
• No cloud-screening implemented
Geometric correction
• Control point source is World Vector Shoreline (source scale 1:250 000) and DCW hydrography (source scale 1:2 000 000)
• Map projection is to Interrupted Goodes Homolosine
Compositing
• Compositing criterion is maximum NDVI
• Compositing period is 10 days
• Compositing limited to solar zenith angles less than 80°
Archiving and distribution
• Permanent archiving of raw data
• Distribution of global 10-day composites electronically and on tape media
• Provision of sub-setting by geographic areas
Data product layers
• AVHRR channels 1–5 scaled to 10-bit range (0–1023) and stored as 16-bit data
• NDVI, illumination and viewing geometry, and date index scaled to and stored as byte data
• Solar zenith angles greater than 80° excluded
• Processed in 10-day composites based on maximum NDVI

(1981) and documented by Teillet 1992a) or Total Ozone Mapping Spectrometer (TOMS) data if available. The atmospheric correction was to allow for atmospheric path length variations due to terrain elevation variations (Teillet 1992b) using data from the GTOPO30, a global digital elevation model with a horizontal grid spacing of 30 arc seconds (approximately 1 km). With respect to image corrections for atmospheric aerosols and water vapour, following very lengthy consideration of the various methods available (Townshend 1992b, Teillet 1994), it was concluded finally that none of the methods had sufficient reliability and/or availability of input data globally to be recommended. Some experts held a minority view, which was not adopted, suggesting that nominal minimum amounts of atmospheric water vapour and aerosol scattering should be assumed and appropriate corrections made on the basis that some water vapour and tropospheric aerosols are always present. It was agreed that the water vapour content estimates made available on a half-degree grid by the US National Meteorological Center (NMC) should be distributed with the G1KA dataset, along with software to allow corrections to be applied as well as appropriate indications of the limitations of the approach, but this recommendation was not implemented. It was also recognized that there is an urgent need for research to develop improved procedures and routinely available atmospheric parameters for atmospheric correction. The inclusion of a cloud mask was recommended, although no particular method was selected. It was proposed that any method adopted should apply a thermal threshold using AVHRR channel 5. In the end, no cloud mask was included in the G1KA product, based primarily on the fact that there was little knowledge of the reliability of such procedures at a 1-km scale. Table 1 summarizes the key implementation features regarding atmospheric correction.

4.3. *Geometric correction*

Because reliable monitoring depends critically on accurate geolocation of imagery, it was recommended that the G1KA product should have a root-mean-square error (RMSE) of 0.8 pixels in relation to known ground control points. The main discussion concerning geometric correction revolved around the relative merits of nearest-neighbour resampling (the approach chosen) versus cubic-convolution resampling. The principal benefits of the former were deemed to be preservation of radiometry and computational simplicity and speed, although it suffers from an effective reduction in location knowledge compared to the latter resampling approach. In keeping with the best practices in geometric image to map rectification (Guertin *et al.* 1985), output pixel locations and inverse co-ordinate transformations were to be used to determine the value in the input image closest to that location. After discussions of a wide range of alternative projections, and following advice from the USGS, the Interrupted Goode Homolosine was recommended. This is an equal area map projection that preserves, to a reasonable degree, the shape of the main continental land masses, with the principal problem being distortion of north-eastern Asia. Its main disadvantage is that there are major breaks in the oceans. A companion recommendation was that software should be included for the relatively simple transformation to Plat-Caree. The key implementation features regarding geometric correction are summarized in table 1.

4.4. *Compositing*

Given the requirement for a globally consistent compositing time period, it was decided that a 10-day compositing period would be used, with resets where necessary to ensure the same calendar dates are used from year to year. The nominal method of temporal compositing is to select the image pixel acquisition with the highest value of the normalized difference vegetation index (NDVI) for each pixel location within the 10-day compositing time window. Information on the generation of NDVI values can be found in Teillet *et al.* (1997a). Alternative selection criteria have been investigated with varying degrees of success (Cihlar *et al.*, 1994a) but they have undergone limited testing so far. Therefore, the maximum NDVI criterion was selected for this initial product generation. The thermal AVHRR values associated with the maximum NDVI are also part of each composite (see section 4.6). However, little work has been done on understanding the information content of the thermal data layers of a temporal composite constructed on the basis of the visible and near-infrared channels. Table 1 summarizes the key implementation features regarding compositing.

4.5. *Archiving and distribution*

Given the importance of long-term data collection, it was strongly recommended that the compilation continue after the 18-month period for the foreseeable future in order to provide continuity with future sensors. Standard CEOS data formats were to be used for all products, which were to also include software to read the data in these formats. The recommended data distribution medium was CD-ROM. However, the data volume of a single global data layer, such as NDVI, exceeds the capacity of a CD-ROM. Therefore, 8-mm tape media are used to distribute the data. Electronic data transfer capability was to be developed, acknowledging that the size of the dataset exceeds the bandwidth available to many users. The key implementation features regarding archiving and distribution are summarized in table 1.

4.6. *Product data layers*

The product specifications call for a processed global dataset to be created, archived and made available at the 1-km scale and with the following data layers processed in 10-day composites in accordance with the recommended procedures. Note that, for any given pixel location, the data layer values are associated with the imagery selected from within the compositing period by the maximum NDVI criterion. The physical scales for the AVHRR data product layers are summarized in table 2.

(1) AVHRR channel 1 (as surface reflectance at 10-bit precision)
(2) AVHRR channel 2 (as surface reflectance at 10-bit precision)
(3) AVHRR channel 3 (as surface radiance at 10-bit precision)
(4) AVHRR channel 4 (as apparent brightness temperature at 10-bit precision)
(5) AVHRR channel 5 (as apparent brightness temperature at 10-bit precision)
(6) Maximum NDVI for the given composite period (at 8-bit precision), where NDVI is computed from at-sensor radiances in AVHRR channels 1 and 2
(7) Solar zenith angle (at 8-bit precision)
(8) Satellite zenith angle (at 8-bit precision)
(9) Relative azimuth angle between solar and satellite directions (at 8-bit precision)

Table 2. Physical and binary scales for G1KA data product layers (DSL, digital signal level). Data are processed in 10-day composites based on maximum NDVI. The mask indicators are as follows: a = 0 for Missing Data Over Land, a = 1 for Ocean, a = 2 for Goode's Interrupted Area, a = 3 is for Solar Zenith Angle Greater Than 80 Degrees; b = 0 for Missing Data Over Land, b = 1 for Ocean, b = 2 for Goode's Interrupted Area. Refer to Eidenshink and Faundeen (1994) for more information.

Layer	Physical units	Quantization bits	Physical value for minimum DSL	Physical value for maximum DSL	Minimum DSL	Maximum DSL	Masks
NDVI	Unitless	8	− 1	1	10	210	a
Satellite zenith angle	Degrees	8	0	180	10	190	b
Solar zenith angle	Degrees	8	0	180	10	190	b
Relative azimuth angle	Degrees	8	0	360	10	190	b
AVHRR channel 1	Percentage reflectance	16	0	100	10	1010	a
AVHRR channel 2	Percentage reflectance	16	0	100	10	1010	a
AVHRR channel 3	Kelvin	16	160	340	10	1018	b
AVHRR channel 4	Kelvin	16	160	340	10	1018	b
AVHRR channel 5	Kelvin	16	160	340	10	1018	b
Date	Index	1	1	245	11	255	b

(10) Date and identification of the source image for the selected NDVI (4-bit precision)
(11) Cloud mask (low number of bits dependent on the procedure adopted)

4.7. *Other considerations*

It was deemed essential that formal links between science groups such as IGBP and the various space and data-processing agencies needed to be established. In particular, IGBP-DIS representatives should be invited to meetings of the relevant CEOS Working Groups and other relevant meetings between agencies and ground receiving station operators. It was also recommended that any significant deviations in the nature of the G1KA dataset should be discussed with members of the IGBP-DIS LCWG, and this was subsequently implemented.

5. Data record and processing status

5.1. *Production status (as of July 1999)*

A global network of HRPT stations, along with data recorded by NOAA, has been acquiring daily global land coverage since 1 April 1 1992. A dataset of over 100 000 AVHRR images has been archived and made available for distribution by EDC and ESA. Based on the processing standards outlined above, a time series of 87 global 10-day maximum NDVI composites has been produced. The 10-day composites span the periods 1 April 1992 to 30 September 1993 and 1 February 1995 to 31 January 1996. NOAA-11 AVHRR data after September 1993 were not processed because of the lateness of the NOAA-11 satellite overpass time. NOAA-14 AVHRR did not become operational until early 1995. Each composite dataset includes the five AVHRR channels, NDVI, three bands of viewing geometry and date-of-observation information. No cloud mask has been included. All of the composite data are available from the DAAC at EDC, and portions are available from ESA.

Table 3 and figure 1 summarize the data product inventory as of July 1999 in various categories, including global composite products, continental subsets of the global composites and level-1b stitched orbit products (dayside portion over land).

5.2. *Data access and distribution status*

Products from the G1KA dataset are provided to users free of charge via the EDC node of the NASA DAAC infrastructure, including provision for access via web interface. Table 4 summarizes the data product formats available in the categories of global composite products, continental subsets of the global composites and level-1b stitched orbit products (dayside portion over land). There has been significant demand for the G1KA dataset, as portrayed graphically in figures 2–7 generated by EDC. Figure 2 shows the number of hits per month on the web site home page for the G1KA dataset in 1996 and 1997. Although such numbers do not reflect the actual number of requests, they are indicative of the dataset's popularity. Figure 3 plots user requests over time for global 10-day composites filled via network distribution. The requests number in the tens of thousands. The subset of these requests that are for 10-day North America composites filled via network distribution is given as a function of time in figure 4. User requests for stitched orbits (as opposed to multitemporal composites) filled via network distribution are given in figure 5. Figures 6 and 7 plot user requests in Gigabytes over time for composite bands filled

Table 3. Data product inventory as of July 1999.

Global composite products

- 1 April 1992 to 30 September 1993 (NOAA-11 AVHRR)
- NOAA-11 AVHRR data after September 1993 not processed because of the lateness of the NOAA-11 overpass time
- 1 February 1995 to 31 January 1996 (NOAA-14 AVHRR)

Continental subsets of the global composites

- North America for 1 April 1992 to 31 March 1993

Level-1b stitched orbit products (dayside portion over land)

- 3600 available on-line for various time periods and locations
- 20 847 in archive

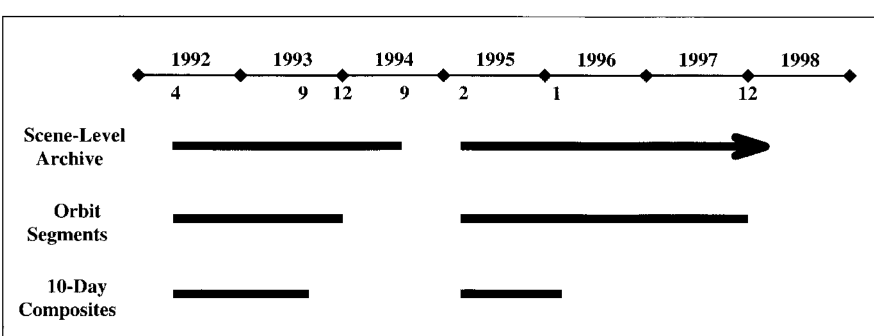

Figure 1. G1KA data availability timeline.

Table 4. Data product formats.

	Electronic file transfer	Tape media
Global composite products	• Spatial and geographic subsets • Data layer by data layer • Can (should) be compressed before transmission	• Low-density 8 mm tape • One data layer per tape
Continental North America composite products	• No subsetting • Can (should) be compressed before transmission	• Low-density 8-mm tape • One data layer per tape
Level-1b stitched orbit products (dayside portion over land)	• Image size is between 70 and 210 Mb, the latter being most of the dayside orbit • Only data coincident with production needs will be available routinely on-line	• 8-mm tape preferred • Multiple scenes per tape

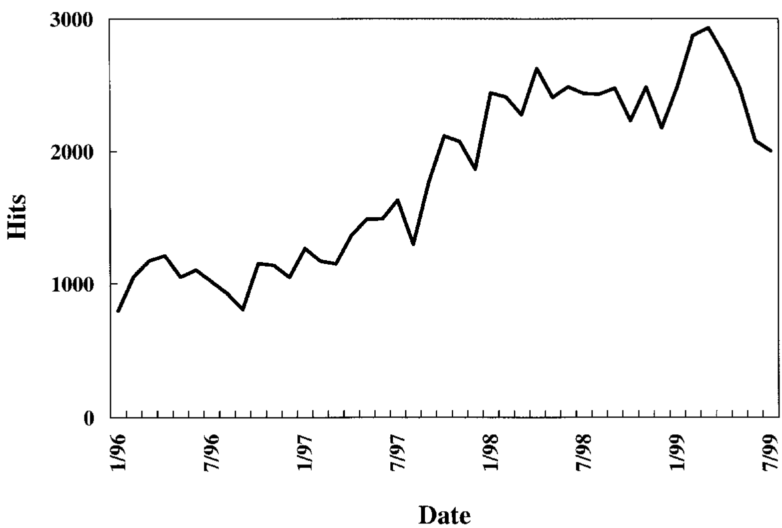

Figure 2. Number of hits per month on web site home page for the global 1-km dataset.

via tape media distribution and for 10-day composites filled via total distribution, respectively. It is clear from the last two figures that the vast majority of data distribution has been via tape media.

6. Current uses of the G1KA dataset

The G1KA data product is critically valuable in current research efforts because the spatial and temporal scales encompassed by the data and their global availability make the product unique (K. P. Gallo 1998, personal communication). The major uses of the global composites currently are related to the study of surface vegetation, mapping land cover and deriving biophysical characteristics of terrestrial ecosystems. Some of the largest G1KA data orders have come from the USA, Italy, the UK, Spain, Belgium and China. This section highlights examples of global and regional uses of the G1KA product, including generation of derived products of global land

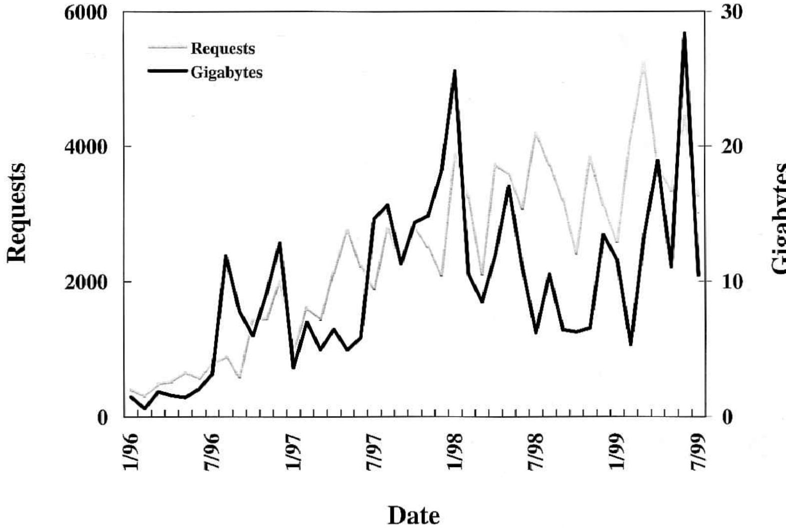

Figure 3. User requests for global 10-day composites filled via network distribution.

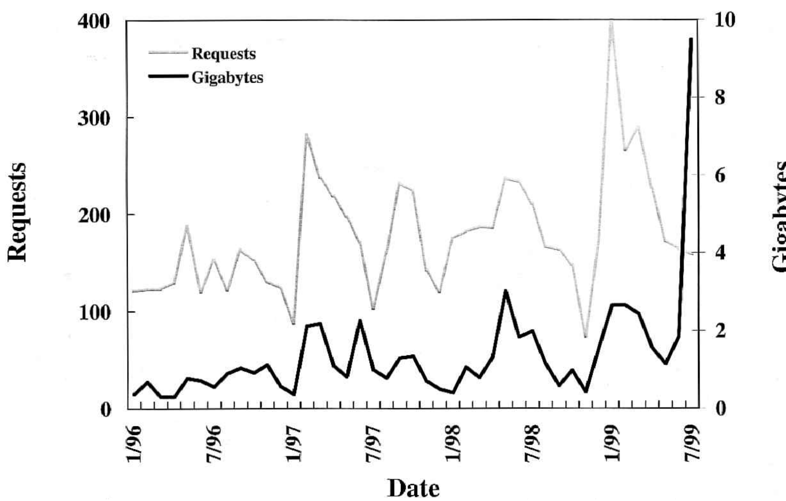

Figure 4. User requests for 10-day North America composites filled via network distribution.

cover (section 6.1), global active fires (section 6.2), and regional research and applications (section 6.3).

6.1. *Global land-cover classification*

Scientists from EDC, the University of Nebraska-Lincoln and the Joint Research Centre (JRC) of the European Commission have generated a 1-km resolution database of global land-cover characteristics (figure 8) for use in a wide range of environmental research and modelling applications (Loveland *et al.* 2000). The land-cover data are derived from the first 12 months of the G1KA dataset (April 1992 to March 1993).

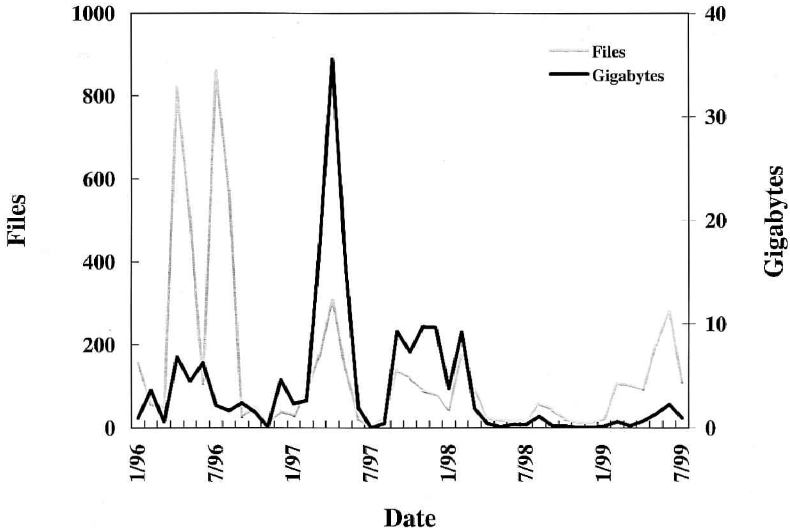

Figure 5. User requests for orbital segments filled via network distribution.

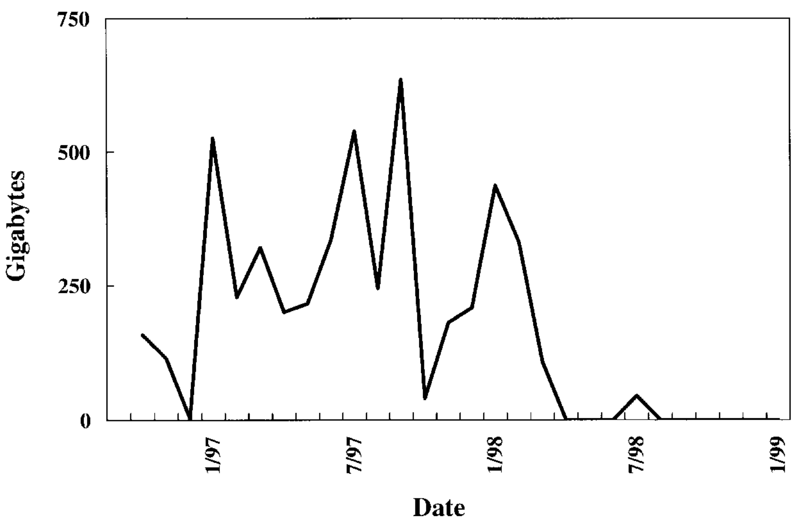

Figure 6. User requests for composite bands filled via tape media distribution.

The dataset depicts regions composed of relatively homogeneous land-cover associations (e.g. similar floristic and physiognomic characteristics) that exhibit distinctive phenology (i.e. onset, peak and seasonal duration of greenness) and have common levels of primary production. In addition, it contains a core set of derived thematic maps depicting six global legends, each representing a different landscape based on a particular classification scheme. One of the schemes, the IGBP's DISCover classification, has been adopted to satisfy the requirements of various IGBP core projects for consistent global land-cover data.

Although maps and models of the Earth's land cover have been created before, they were not capable of such fine detail, nor were they as useful for measuring significant changes because they lacked the consistency and timeliness characteristic

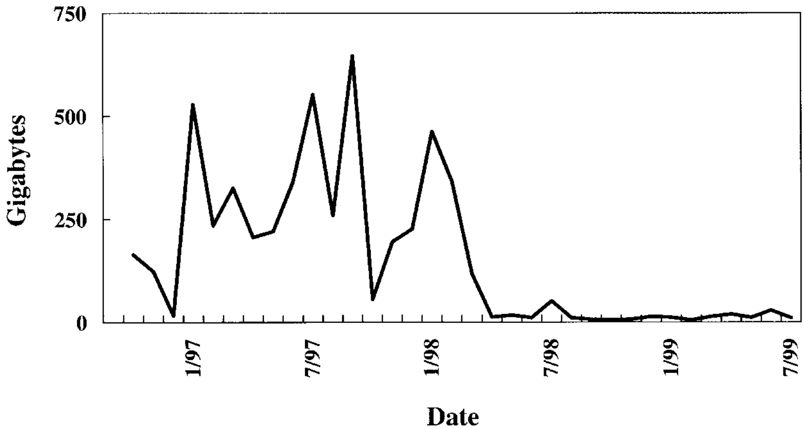

Figure 7. User requests for 10-day composites filled via total distribution.

of data from a uniform source—AVHRR in this case. To date, users from over 60 countries are using these data for applications that fall into four major categories: mapping, modelling, conservation and general interest. The entire database is available at no charge from the NASA Land Processes DAAC at EDC.

More recently, two global land-cover products have been created by researchers at the University of Maryland. The first represents land cover in terms of traditional land-cover classes (Hansen *et al.* 2000) in a similar way to the product of Loveland *et al.* (2000). In the second product, land cover is represented by percentage cover of key attributes such as woody and herbaceous cover (DeFries *et al.* 1999). In a further development, the cover classes defined in the first product are used to modify the mixture modelling equations to generate a global product of forest cover at the 1-km scale (DeFries and Townshend 2000).

6.2. *Global fire product*

In an early assessment of data gaps for global change research, the IGBP Core Projects on atmospheric chemistry and terrestrial ecology identified global fire distributions as a priority dataset. The IGBP-DIS Fire Working Group was established in 1993 to develop the international collaboration needed to produce a 'fast-track' global fire product at the 1-km scale. The Working Group recognized the utility of the G1KA dataset for generating active fire datasets and embarked on a series of workshops to develop a community consensus algorithm for AVHRR fire detection and data product specifications. The algorithm selected uses the middle and thermal infrared channel data from the AVHRR and is described by Eva and Flasse (1996) and Kendall *et al.* (1997).

The JRC at Ispra, Italy, stepped forward to provide the generation of a global active fire dataset, using the level-1b data collected through the G1KA project. At the time of this writing, 12 months of active fire data have been generated and are available through JRC (http://www.mtv.sai.jrc.it/projects/fire/gfp/home.html). An example of the product is shown in figure 9. The fire dataset is being used in a number of studies associated with trace gas emissions, atmospheric chemistry and land-cover changes.

The global AVHRR active fire product has provided a prototype for new and

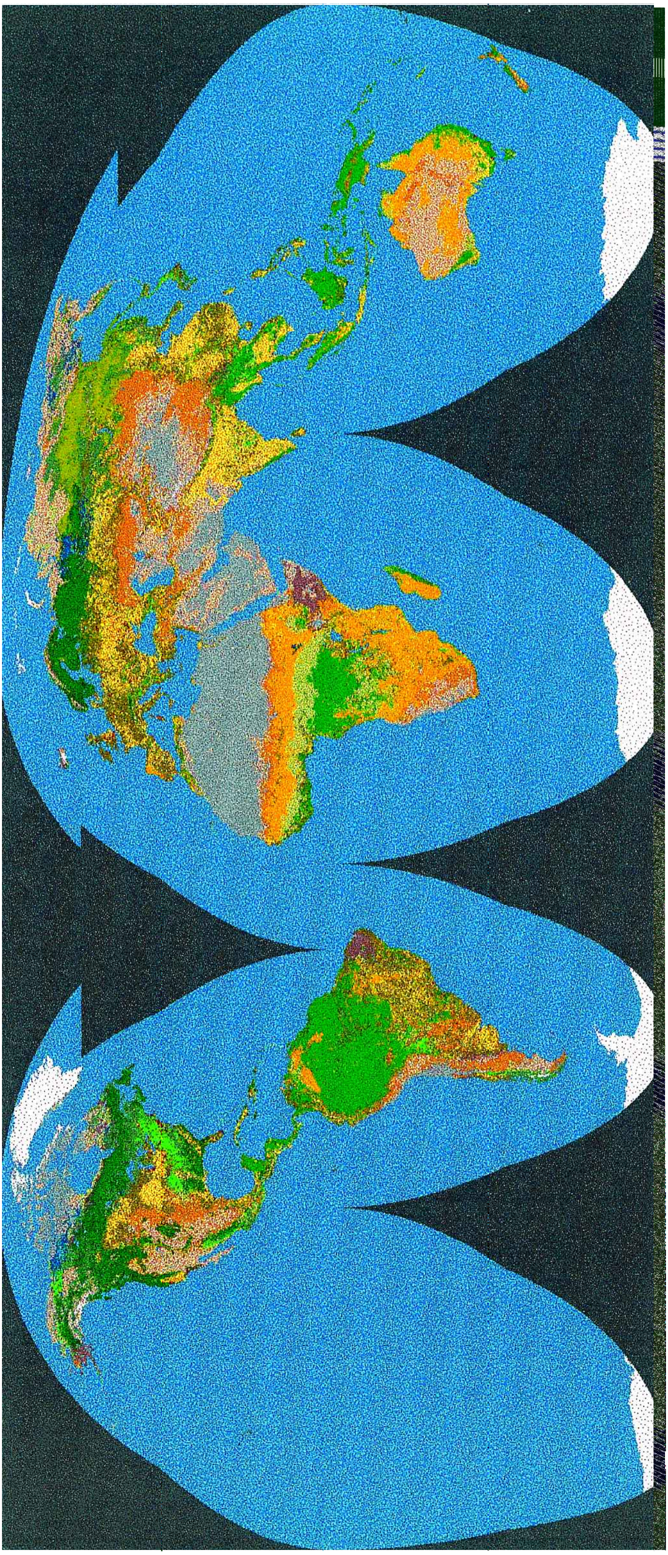

Figure 8. Global land cover at 1-km scale (see Loveland *et al.* (2000) for details). The land-cover data are derived from the first 12 months of the G1KA dataset (April 1992 to March 1993).

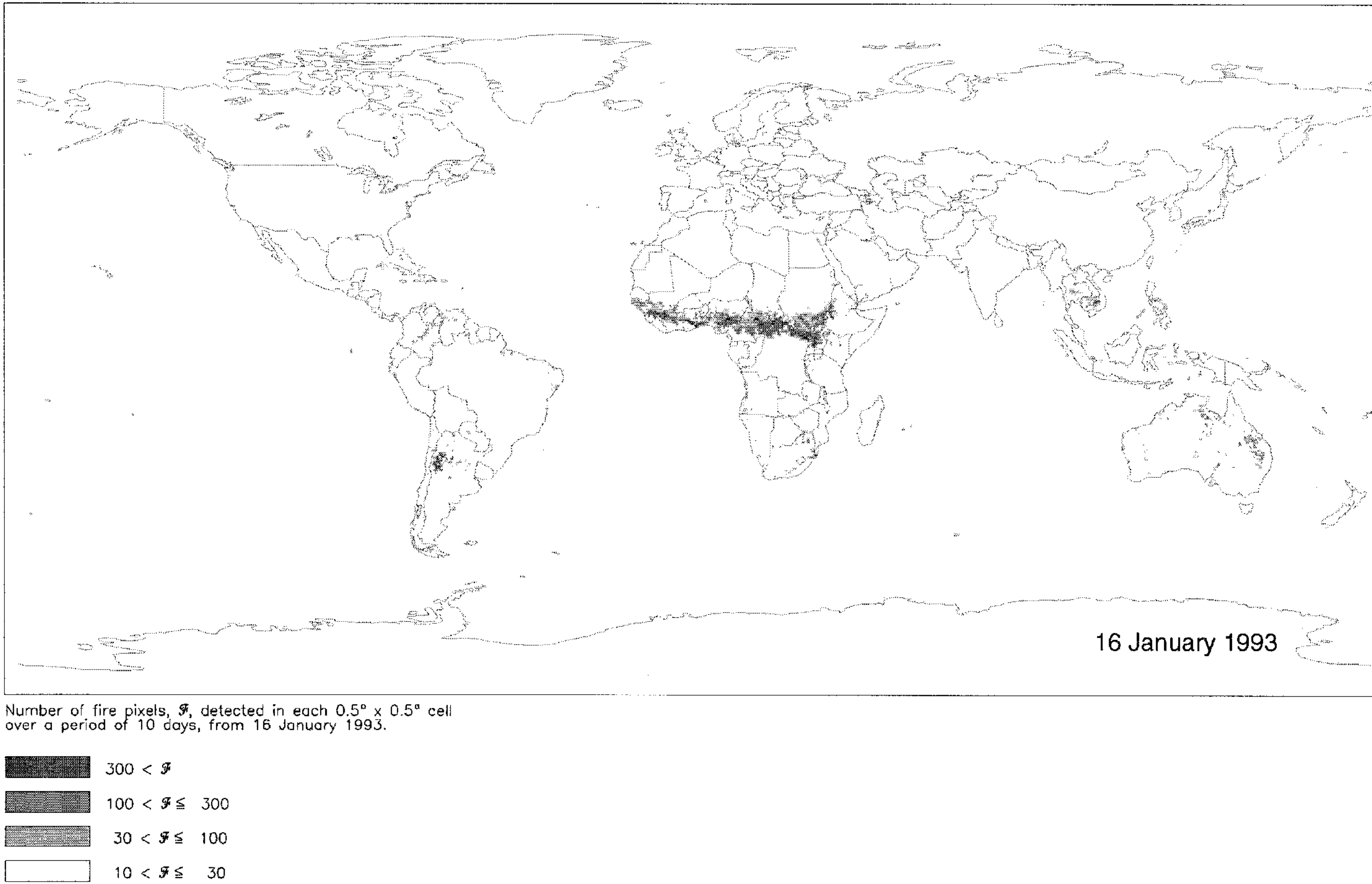

Figure 9. The global fire product portraying the number of active pixels for the 10-day period starting 16 January 1993.

improved fire datasets from the AVHRR and new sensing systems such as the ESA ATSR (Eva *et al.* 1995) and MODIS (Justice *et al.* 1998).

6.3. *Regional research and applications*

Regional research and applications examples were submitted by various investigators during the G1KA evaluation process. The examples fall primarily in the categories of energy balance, ecosystems and land cover, and they include studies of desert land forms, woodlands classification, geothermal zoning, urban heat island effects and a variety of mapping applications.

Gallo and Huang (1998a) have compared the G1KA dataset to values from the global NOAA/NASA GAC Pathfinder AVHRR Land (PAL) dataset at coincident temporal and spatial scales ($10° \times 10°$ cells). Despite differences in the original spatial scales (1 km for the G1KA and 8 km for the PAL) and data availability and, hence, satellite zenith angles, NDVI values from both datasets are very similar. As part of a follow-on regional analysis (Gallo and Huang 1998b), the authors note that probable cloud contamination has led to anomalous NDVI values of zero in the G1KA dataset for composite number 28 (1–10 January 1993) for the south-eastern USA and composite number 26 (11–20 December 1992) for south-eastern Australia.

7. Evaluation of specific processing components

The 1-km AVHRR dataset project of the IGBP-DIS has distributed a significant volume of data to the global change science community and non-research users. The original objectives of the project have been achieved by providing a new global database and a basis for the development of higher-level products of land cover and fire distribution, among others. The G1KA dataset development process is now complete, and an informal evaluation of the dataset has been carried out. The purpose of the evaluation was fourfold:

(1) to assess the dataset relative to product specifications;
(2) to assess the dataset relative to product utilization;
(3) to identify and document characteristics of the dataset affecting data use; and
(4) to provide input to decisions on retrospective refinements or reprocessing of the dataset and on future options for archiving and processing activities.

Several times during 1997, the IGBP-DIS solicited inputs from the user community for this evaluation with limited success. Various factors could be involved in the modest response. Although requests for inputs were distributed widely, many parts of the world have less ready access to communications via electronic means, despite having been able to obtain data. However, it is most likely that individuals and agencies have been keen to order datasets but have had less time or motivation to provide feedback on a voluntary basis. A lesson learned here is that user profiles vary considerably, and there is a need for mechanisms to track users unobtrusively and obtain their feedback.

Because of the modest number of inputs received (approximately 15 documents), it was decided to hold a workshop in April 1998 in Washington, DC, to complete the evaluation synthesis and prepare the outline of this paper. The following sections summarize the main points gleaned from the reports, letters, electronic mail and personal communications received on the use of the G1KA datasets in various settings and augmented by the workshop discussions. In general terms, processing of the G1KA dataset as implemented has proven to be highly compliant with respect to the processing specifications described above. Some of the problems identified have been resolved, but many of the remaining deficiencies concern shortcomings and needed improvements in the state-of-the-art in quantitative processing of Earth observation data.

7.1. *Sensor radiometric calibration*

As noted in section 4.1, the sensor radiometric calibration of AVHRR channel 1 and 2 data involved in the G1KA product has been based on the best available coefficients at the time of processing. However, there has been no accuracy assessment or analysis of the impact of calibration uncertainties on the product. There is justification for an on-going concern for and efforts towards the long-term continuity of radiometric calibration and data product consistency with respect to datasets from different AVHRR sensors, as well as from the more advanced sensors becoming available.

For calibration of the thermal channels, inconsistencies in the non-linear corrections over product lifetime have been identified, giving rise to too many false fire detections in the global forest fire product. Improvements can be expected if the non-linearity corrections are applied to brightness temperatures instead of to radiances.

7.2. *Atmospheric correction*

The atmospheric correction in the processing of AVHRR channel 1 and 2 data for the G1KA dataset was limited by design (see section 4.2). It was not expected to provide accurate surface reflectances except in the clearest atmospheric conditions with minimal aerosol and water vapour effects. The atmospheric correction algorithm does take terrain elevation into account but does not allow for surface reflectance anisotropies. The literature reports no validation investigations regarding G1KA channel 1 and 2 surface reflectances and NDVI, although such work is admittedly difficult given the 1-km scale and global spatial extent involved.

Compensation for atmospheric effects in satellite sensor imagery is clearly an indispensable component in the process of surface reflectance retrieval. However, the current status of atmospheric correction is that it is not operational. In addition to the need for image data that are very well calibrated radiometrically, the most important key to more routine atmospheric correction is timely and ready access to information on atmospheric variables such as aerosol optical depth and atmospheric water vapour content for input to atmospheric codes (Teillet 1997). For example, it should now be feasible to implement corrections for water vapour absorption effects using on-line information currently available on atmospheric water vapour content from NASA's Data Assimilation Office (DAO). If data gaps are to be filled using climatological data, a clear-sky water vapour climatology should be used (K. P. Gallo 1998, personal communication). More pertinent climatological ozone data should also be available. Consideration would should be given to a retrospective correction in this regard in order to maintain compatibility between past and current datasets. Similarly, it should also be possible now to implement improved Rayleigh corrections using globally available surface pressure data.

Image corrections for tropospheric aerosols over land on a global basis remain a difficulty, but with the advent of global aerosol products from the EOS MODIS and other sensors in the near future the necessary data assimilation should become possible. Stratospheric aerosols such as those produced by the volcanic eruption of Mount Pinatubo in 1991 have a significant impact on the surface reflectance and NDVI products. For instance, 2 months after the eruption of Pinatubo, a dust layer had formed 20 km above the Earth's surface where the largest optical depth observed was 0.4–0.6 at 0.55 μm (Vermote *et al.* 1997). Unlike the situation for other atmospheric effects, the effect of stratospheric aerosols is not reduced by temporal compositing because of their persistence and long lifetime (Bluth *et al.* 1992). For example, NDVI monthly composites (generally bounded between -0.1 and 0.6) showed a systematic decrease of approximately 0.15 in NDVI 2 months after the eruption of Pinatubo (Vermote *et al.* 1997). A procedure based on deriving stratospheric aerosol optical depth over the Pacific Ocean was developed by Vermote *et al.* (1997) for correction of AVHRR spectral bands 1 and 2. The procedure is currently used in the production of the Global Inventory, Modeling and Monitoring System (GIMMS) datasets at NASA/GSFC (C. J. Tucker 1998, personal communication). Results from this approach and the availability of satellite and model derived stratospheric aerosol fields, such as those available at NASA Goddard Institute for Space Studies (GISS) (Sato *et al.* 1993, Hansen *et al.* 1996), make the stratospheric aerosol correction feasible for future editions of the G1KA dataset.

7.3. *Spectral characterization*

Although it receives relatively less attention than sensor radiometric calibration and atmospheric correction, spectral characterization is an important aspect of surface reflectance retrieval, regardless of how wide or narrow the spectral bands may be. The impacts of inadequate spectral characterization have not been addressed in the evaluation of the G1KA data product. The spectral response profiles of the AVHRR sensors involved are similar, and so significant effects are not expected. However, studies have indicated potentially very significant differences between NDVI values derived from other sensors with different spectral channel characteristics, such as MODIS for example, and/or due to changes in spectral channel responses during on-orbit operations (Teillet *et al.* 1997a). Clearly, if the spectral bands have changed in position or width or there are uncertainties as to their characteristics, there is a direct impact on radiometric and atmospheric processing, as well as on data and information products (Suits *et al.* 1988, Teillet 1990b, Flittner and Slater 1991).

Long-term land-cover data records in general, and vegetation indices in particular, will span the lifetime of multiple sensors of a given type and also encompass several different sensor types. Nevertheless, study of the impact of radiometric, spectral, and spatial sensor characteristics on such indices has only begun recently (Guyot and Gu 1994, Qi *et al.* 1994, Teillet *et al.* 1997a). One faces the important and difficult task of ensuring that the same vegetation information can be obtained from all of these sensor systems. The key perspective to adopt for the future is that spectral characteristics of sensors should be sufficiently well understood and characterized to allow the generation of similar geophysical and biophysical products from dissimilar measurement methods and systems.

7.4. *Geometric effects on image radiometry*

Another area that has received relatively less attention is that of the role of geometry on image radiometry. It is true that bi-directional reflectance effects have been studied extensively, but they remain challenging to deal with in an operational setting, and there are many other geometric effects to consider. The anisotropy of surface reflectance as a function of illumination and viewing geometry is best described in terms of the bi-directional reflectance distribution function (BRDF). In the analysis of remotely sensed data, BRDF effects should be taken into consideration, by correcting for them where necessary and/or by taking advantage of anisotropic behaviour to improve target discrimination. BRDF artefacts have been observed in AVHRR channels 1 and 2 of the G1KA composites, even after sensor radiometric calibration and atmospheric correction. The BRDF can be modelled, but it is presently impractical to apply models that are land-cover type-specific on a global basis, although this may become possible in the future (see, for example, Li *et al.* (1996) and Cihlar *et al.* (1994b)). Even approximate BRDF information for broad classes of land cover can improve atmospheric correction computations (Kaufman *et al.* 1997).

As is typical for AVHRR data, the G1KA data product has a high percentage of pixels within $\pm 40\%$ of the solar principal plane (Yang *et al.* 1996, Zhu and Yang 1996). Also, Earth observation data acquisition on a nearly daily basis necessarily encompasses very low sun angles (large solar zenith angles) a significant percentage of the time. For North America in the October–February time period, 10% or more (peaking at 42% in December) of the area covered by AVHRR data has solar zenith angles greater than 80° (Zhu and Yang 1996). For many land-cover types, this will give rise to very low surface reflectances. Also, at large scan angles in the forward scattering direction, very large solar zenith angle geometries can lead to a significant increase in scattered light in the AVHRR sensor. Moreover, the atmospheric correction algorithm adopted for the G1KA project is known to be less accurate at large solar zenith and satellite zenith angles. For these reasons, data processing for the G1KA dataset excluded solar zenith angles beyond 80°. Masking out solar zenith angles greater than 80° has led to significant data omissions, 0–42% according to Yang *et al.* (1996) and Zhu and Yang (1996), the worst case being in December 1992 in North America. However, it is not known how many of these pixels would be selected in the compositing process if they were to be available for selection.

Increasingly, users will be integrating data from different Earth observation systems and from different non-remote-sensing sources, most if not all of which sample the Earth's surface in very specific modes and geometries that have direct impact on the radiometric character and information content of derived products. For AVHRR, panoramic distortion and Earth curvature transform 1.1-km nadir pixels to ever larger and overlapping footprints as a function of scan angle, reaching dimensions of about $1.5\,km \times 2.5\,km$ at scan angles of $\pm 45°$ and about $2\,km \times 5\,km$ at scan-angle extremes of $\pm 55°$. The solution to this problem has generally been to avoid using AVHRR data beyond about 40° off nadir for quantitative analysis. A satellite zenith angle cut-off of 42° has been used in the G1KA processing stream. In addition, due to the AVHRR's modulation transfer function, even nadir pixels receive less than half of their integrated signal from a 1.1-km circular footprint. In the G1KA composite data layers, the intrinsic spatial resolution cannot be inferred from the position of a pixel in the 1-km scale product because temporal composites include data from different AVHRR image acquisitions and hence different view angle geometries. Speckle and blurring are evident in some multitemporal products, indicating possible problems in image registration and/or the variability of ground sampling resolution. An argument can be made in favour of a recommendation to users to use caution in interpreting analysis products from the G1KA datasets at the 1-km scale and to consider generating final information products at scales in the range of 2–4 km.

Also of concern is the selection of an image resampling kernel. The nearest-neighbour resampling approach used for the G1KA datasets was selected ostensibly to preserve the radiometric character of the imaged terrain. It can be argued that, given the gridded nature of rectified image space and also the topographic variations in some locations, nearest-neighbour resampling will actually give rise to an incorrect spatial distribution of the terrain's radiometric information content (B. Guindon 1991, personal communication).

The lack of global availability of terrain elevation data at sufficiently high spatial resolution precludes the possibility of image corrections for topographic slope-aspect effects in areas or rugged relief (Teillet and Staenz 1992, Running *et al.* 1994).

7.5. *Geometric considerations*

Geometric correction involves precise transformation of the image from the sensor-based co-ordinate system to an Earth surface-based projection. This process includes calculation of a satellite model, matching ground and image-based control points and transformation and resampling the data to a map projection co-ordinate system, the Interrupted Goode Homolosine in the case of the G1KA product. The geometric correction implemented for G1KA data processing includes control-point matching and terrain-elevation correction with respect to the geoid. The digital terrain elevation data (DTED) set used for the latter correction is GTOPO30, which has a horizontal grid spacing of 30 arc seconds (approximately 1 km). Control points for AVHRR data are commonly identifiable features along coastlines, lakes and rivers. Some prominent physiographic features are used in arid regions where hydrologic features are sparse. Various approaches are used to facilitate control point identification and matching (Eidenshink and Faundeen 1994), including the use of satellite image chips (preferably at higher spatial resolution) or vector datasets such as the Digital Chart of the World (DCW) or the World Vector Shoreline (WVS).

There are visible seams in the data along the edges between Goode projection sections, as well as along scene boundaries, even in the NDVI data layer (figure 10). For some regions, such as central Africa, the equator is visible in nearly all annual metrics, and the Mollweide–Sinusoidal boundary is also clearly evident in many of the datasets (R. De Fries 1998, personal communication). Such artefacts leave strong negative impressions with users and have undesirable effects on any subsequent quantitative analyses. Apparently, the seams can arise from discarding image swath portions with an insufficient number of ground control points, due to clouds for example, or from a lack of data availability due to locations of ground receiving stations. Resolution of this problem would greatly enhance the usability of the G1KA product. The use of Interrupted Goode Homolosine projection and nearest-neighbour resampling also leads to image area expansion in many locations or image area reduction in few locations, resulting in significant data duplications or losses (Yang *et al.* 1996, Zhu and Yang 1996). Shoreline movements have also been observed (e.g., Lake Baykal) (R. De Fries 1998, personal communication), but there would be insufficient benefit to warrant the removal of the water mask built into the land data product.

For G1KA geometric processing, the recommended geolocation accuracy was 800 m RMSE; actual results vary from 700 to 1300 m. Experience to date indicates that extended water bodies, cloud cover and snow cover lead to automated scene

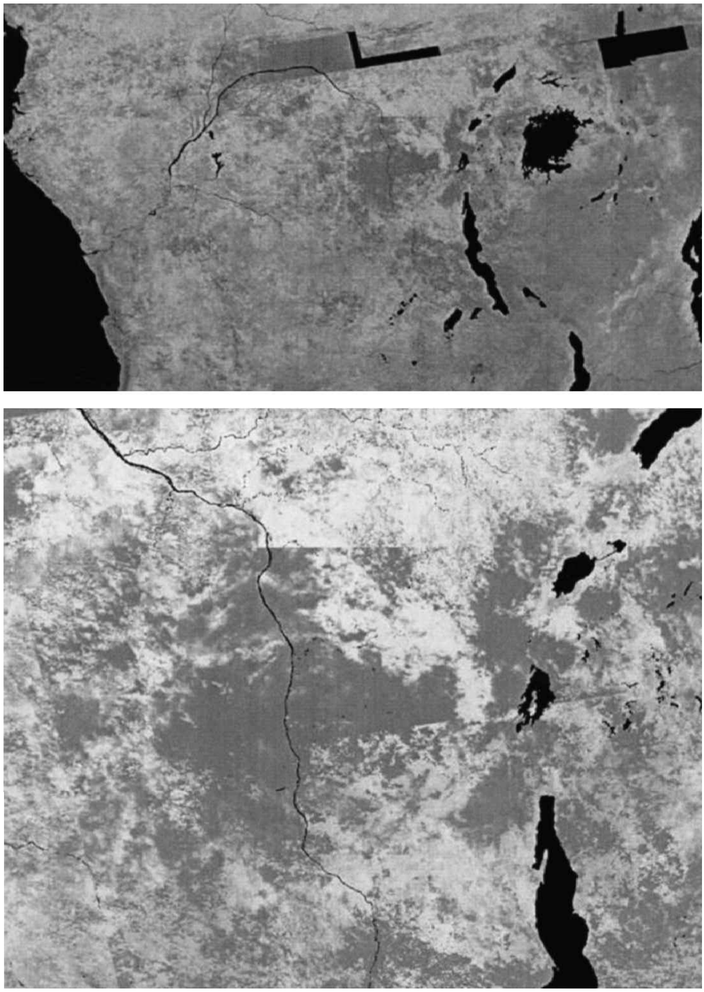

Figure 10. Examples of seams in a 10-day composite (1–10 November 1995). The figures show seams due to lack of data and/or failure to navigate the orbit segment (along the orbit edge and across the orbit), as well as a horizontal seam at the equator that is an artefact of the processing approach. The co-ordinates of the upper image are 5°N 9°E for the upper left corner and 10°S 32°E for the lower right corner. The lower image is the sub-area delimited by 2°N 21°E and 6°S 32°E.

registration failures due to inadequate distribution of control points. The scene rejection rate from automated G1KA processing is approximately 40% (manual follow-up reduces this to approximately 25%).

EDC has been responsive and able to fix many of the geometric problems identified in the G1KA data. Compared with early processing, geometric registration has improved and become more consistent; seams are generally less prevalent except where data access has been reduced. EDC is in the process of obtaining an improved orbital propagator and better ephemeris information that will, once implemented, improve the registration probability for scenes that have cloud cover and improve the accuracy of those scenes. Construction of control chips from higher-spatial-resolution imagery, such as Landsat Multispectral Scanner (MSS) data, will improve the performance and accuracy of image to image correlation. Other refinements in the satellite and sensors model and the control-point fitting process are expected to improve overall accuracy.

It is estimated that, at best, 40% of the data can be registered using ground control points. The rest of the data are too cloudy overall to get good control point distributions. If improved methods could lead to a reduced reliance on control points while maintaining geometric accuracy, the success rate would in principal increase to near 100%. However, there is no evidence, quantified over large numbers of images over large geographic areas for a wide range of cloud cover, indicating that geometric registration accuracies achieved to date can be maintained for 1-km data without ground control points.

7.6. *Compositing and processing issues*

There has been negligible feedback on the use of a 10-day compositing period based on maximum NDVI criterion. It has been concluded that 8-bit precision for the NDVI data layer is sufficient (Eidenshink and Faundeen 1994). It should also be noted that NDVI is best computed from reflectances rather than radiances (Teillet *et al.* 1997a). Some investigators have determined that there is a bias in G1KA composite data toward the forward scattering direction for North America (winter months) and a fairly uniform scattering angle distribution around nadir for South America (Yang *et al.* 1996, Zhu and Yang 1996). There are no apparent latitude biases for the Americas, whereas there are some longitude biases but they are not consistent at all latitudes or locations (further study is required).

There have been cases of apparently misplaced swaths in G1KA composites, which have required manual editing by the user to remove them from the dataset in order to avoid errors in the final land-cover map. However, visual inspection of all composites in all places is beyond the resources of users, and the resulting errors are often only identified in the final classified product.

With the maximum NDVI criterion for temporal compositing, misregistration errors create problems along boundaries. The effect is to overestimate vegetated areas along any class boundary and thus generate a buffer of the greener class. For example, grasslands within the Amazon forest are smaller in area in the G1KA data compared to surface areas obtained from high-spatial-resolution imagery. Similarly, in mosaicked regions including forest and non-forest classes, the forest area is overestimated. While this problem cannot be overcome entirely, a greater proportion of observations near nadir and improved geolocation accuracies would help to reduce it.

The processing flow for the G1KA product has been described by Eidenshink and Faundeen (1994). The issue of the processing sequence for the atmospheric correction relative to temporal compositing is highlighted here. Ideally, atmospheric correction should be applied to the imagery prior to temporal NDVI compositing in order to optimize the image data available for selection in the compositing process. However, Cihlar and Huang (1994) have shown that using atmospherically corrected data in the maximum NDVI compositing process can increase the probability of selecting pixels with higher satellite zenith angles and more likely in the backscatter direction. These findings and the desirability of applying improved atmospheric corrections in future without having to repeat the whole processing sequence led to the decision to apply the atmospheric correction after the compositing process (Eidenshink and Faundeen 1994).

7.7. *Archiving and distribution issues*

While some users have experienced occasional problems in the early days of the G1KA product in downloading the data from EDC or receiving 8-mm tape data orders (R. De Fries 1998, personal communication), users have found more recently that the process is generally straightforward and uncomplicated (K. P. Gallo 1998, personal communication). Some users with commercial image analysis systems would appreciate the availability of other image format options for ease of use (K. E. Ryavec 1998, personal communication).

For global change research, the timeliness of data availability is not a strong limiting factor presently. However, that will likely change once data from several new sensors will be available, and timely comparisons between the G1KA product and datasets from the new sensors will be of great interest and utility.

From the user perspective, the value of AVHRR 1-km data has been established for some time. The innovation with the G1KA product is its global nature, and with it comes data handling issues that users must face: the data cost is low but equipment costs are less trivial and managing global datasets is not easy. Nevertheless, the AVHRR data have been rendered much more accessible and usable in their digested form, since most users would not have gone through the effort to acquire and process large amounts of raw data (K. De Ridder 1998, personal communication).

7.8. *Other issues*

The composited AVHRR channel 1–5 data layers appear to have significant variability, possibly due to many of the uncorrected or inadequately corrected effects described in previous sections, such that land-cover patterns are often less evident. The NDVI data layer is less affected and consequently provides more meaningful time-series profiles for further analysis. Annual metrics not dependent on ordered time series have been derived, and some have been found to be globally meaningful, such as minimum annual AVHRR channel 1. Low red reflectances during the growing season yield good woody/non-woody discrimination. Similarly, metrics that are based on the thermal channels and exploit the high-temperature months provide useful information for discriminating land-cover types, including latitudinal stratification of needle and broadleaf forest, as well as separation of tropical woodlands from forests.

The problem of shifting equatorial crossing times for the NOAA satellites has not been examined in the evaluation of the G1KA dataset. However, it has been noted that inclusion of only afternoon data precludes thermal inertia or day–night temperature difference studies (J. A. Sobrino 1998, personal communication).

When the G1KA data product has been changed or improved, it is important to inform the user community in an effective and timely way.

8. Options for improvements

8.1. *Data correction and processing*

With advances in processing since the beginnings of the G1KA project and the experience gained in the generation, handling and evaluation of the G1KA datasets, many improved data correction and processing methods have been identified (El Saleous *et al.* 2000). These improvements are highly recommended as they can benefit not only the AVHRR datasets but also provide very useful knowledge for the processing of global data from other satellite sensor systems.

For radiometric processing, the best available sensor radiometric calibration coefficients should be obtained from the relevant experts. A proper non-linearity correction for thermal infrared channel calibration should also be implemented. It has been suggested that the solar zenith angle mask be removed so that all data are included and that users be provided with suitable QA flags and caveats about the use of data at very large solar zenith angles. The feasibility of providing a cloud mask also needs to be considered.

Compared to past data-correction procedures, more advanced atmospheric corrections can be implemented, including:

- improved Rayleigh scattering correction based on globally available surface pressure data from the DAO instead of terrain elevation data and climatological profiles;
- ozone absorption correction based on best data available instead of climatological data;
- water vapour absorption correction based on DAO data instead of no correction; and
- correction for stratospheric aerosol scattering effects instead of no correction.

While atmospheric corrections for tropospheric aerosol scattering effects remain difficult, they are under active investigation in programs such as the EOS MODIS, and the possibility of aerosol corrections for the G1KA datasets should be investigated and hooks at least should be built into the processing stream for eventual implementation. A revisit of the issue of processing sequence with respect to atmospheric correction and compositing is also warranted.

More advanced navigation methods can lead to reduced percentages of data lost and increased cloud-free observations. It would also be practical to implement map projection capability to go from the Goodes to other common projections.

Any new implementations should incorporate the generation and availability of automated QA flags wherever appropriate.

Recent research on alternative compositing should be considered in any reprocessing of the data. Research on different compositing criteria has not been as extensive as it should be, and such investigations would be of great interest with the advent of new remote sensing data sources.

8.2. *Main scientific drivers*

Reprocessing and continuation of the G1KA dataset is justified on the basis of several scientific drivers:

- the scientific requirements summarized in section 3;
- the usefulness of detailed yet global land-cover mapping and characterization;
- the potential to monitor seasonal/interannual change;
- analysis of El Nino and La Nina events of 1997 and 1998;
- overlap with the data record and products from MODIS and other satellite sensors;
- data extension to the NPOESS era.

A consistent, long-term data record is achievable in various ways, including the generation of continuous or discontinuous data records and, in the case of continuous measurements involving different sensors, overlapping data products. The distinction can also be made between time-series continuity of raw data, algorithms and information products.

8.2.1. *Land-cover mapping and characterization*

The process of land-cover classification/mapping, characterization (including seasonal/inter-annual behaviour) and parameterization (for model use) requires multi-annual datasets of some kind. This process is deemed to be essential because land cover and land use are key drivers in the context of global change and biogeochemical cycles. The biggest obstacle to improved land-cover classification is the quality of the input data. Other questions that arise are whether this process needs to be done at the 1-km scale, whether it needs to be done periodically or on a continuous basis and whether retrospective data reprocessing as far back in time as possible is required for this purpose.

The operational success of programs such as the Global Observation of Forest Cover (GOFC) program, initiated by CEOS as part of its Integrated Global Observing Strategy (IGOS), depends critically on a long-term commitment to global image data of forest cover at the scales of 250–1 km (Ahern *et al.* 1998a,b).

8.2.2. *Seasonal/interannual change*

It is less clear whether land-cover change detection and quantification require continuous G1KA datasets. At the 1-km scale, comparisons could be made between, say, 1992 and 1999 (a quasi-decadal time period), without necessarily examining intervening years; however, there is no assurance that any given year alone provides a proper baseline, and so a few consecutive years would be needed each decade regardless. Another option that would supplement the continuous global work would be regional comparisons between 1982 (or 1985) and 1999 for key regions such the Sahel, southern Africa, south-east Asia, North America and Europe (readable HRPT archives would have to be mined). Such a data rescue mission would be logistically challenging for some regions.

An argument can be made that coarser-scale data (such as the 8-km data) would be inadequate to address seasonal and inter-annual phenological change requirements. Certainly, the G1KA dataset is the most detailed database from the early 1990s, and it can make a unique contribution. Study of regional impacts does require at least a 1-km scale or better, and databases could be constructed to assess degradation and productivity issues of regional interest. However, it is worth noting that processing and handling many regional datasets would likely require more resources than does the preparation of global datasets. Global datasets also provide consistency of processing and, moreover, continuous time series would provide a background reference data record. In any event, virtually all land regions of the globe have environmental concerns now, even the Polar regions.

8.2.3. *Future mission profiles*

A variety of Earth observation sensors have been launched in recent years, and several more will follow in the near future. These missions can be categorized into three mission types:

(1) process studies (involving sensors with special features such as the directional capability of the EOS Multi-angle Imaging Spectroradiometer (MISR));
(2) research, long-term measurements (involving high-quality broad-scale sensors such as the EOS MODIS); and
(3) operational, long-term measurements (involving an on-going series of operational sensors such as the NPOESS).

Sensors in the second and third categories are the ones that can contribute to the generation of a long-term global data record at the 1-km scale. In principle, these would include the currently available NOAA-14 AVHRR, SeaWiFS (Sea-viewing Wide Field-of-view Sensor), ERS-2 ATSR and SPOT-4 VGT, as well as the forthcoming EOS MODIS, Envisat MERIS and AATSR, ADEOS-2 GLI and NPOESS. However, experience with the harmonization of large collections of data products generated from a multiplicity of sensors has been limited to date (Teillet 1997, Teillet *et al.* 1997b). Thus, the greatest effort should be directed towards the use of series of the same or very similar sensors, hence primarily the operational NOAA satellite sensors, but also the EOS MODIS sensors. Single mission sensors can potentially be used to fill spatial or temporal data gaps or help to address special research questions regarding the generation of long-term data records from Earth observation. In all cases, the proper characterization of each individual sensor is essential, including efforts undertaken pre-launch (full characterization), post-launch (geometric and radiometric performance monitoring) and over the lifetime of the sensor (mainly radiometric calibration). Moreover, during the transition between sensors, inter-sensor calibration and overlapping observations are crucial.

8.2.4. *Overlap with EOS MODIS*

Long-term continuity of the G1KA data record is most likely to be accomplished on the basis of some combination of measurements from multiple instruments, e.g. the NOAA AVHRR, SPOT VGT, EOS MODIS and NPOESS suite of sensors. AVHRR–MODIS overlap and data continuity can enhance the immediate value of MODIS data, add a long-term temporal framework to EOS data records and provide a means for new sensor evaluation. Continued AVHRR global datasets at the 1-km scale also provide a reliable source of data as well as a backup capability in the unfortunate event of a MODIS failure and in view of the known delays in the EOS Data and Information System (EOSDIS).

AVHRR data will be needed as part of the shakedown. The length of the overlap period should be a minimum of 1 year, and 2 years would be preferable, to allow seasonal and time-series analyses. If the 2-year period including 2000 and 2001 were to constitute the AVHRR–MODIS overlap period, for example, and AVHRR data processing goes back to 1995, then a 7-year AVHRR data record would be available, including a 2-year overlap with MODIS data. Such an overlap period would allow for the development of algorithms that ensure not only geophysical data continuity but higher-level product continuity as well.

9. Recommendations

The following recommendations are made on the basis of the evaluation of the G1KA dataset.

9.1. *Recommendations to agencies responsible for the production of the G1KA data record (primarily ESA, NASA, NOAA, and USGS)*

Recommendations regarding the G1KA data record are as follows.

(1) Localized gaps in the record have been found and there are a very small number of known misplaced parts of images (section 7.6). The existing historical G1KA data record should be reprocessed to correct these errors. Corrections should extend back to the beginning of the NOAA-14 AVHRR data record in 1995. Additionally, the NOAA-11 AVHRR record should be similarly reprocessed up to the end of September 1992. After that date, the

increasing lateness of the NOAA-11 overpass time means that the data will have very little value for terrestrial monitoring, and preprocessing is not recommended. The highest priority must be to fix those problems leading to low-quality composites, so that the latter can be replaced wherever possible.

(2) Production of a second-generation edition of the G1KA dataset should be carried out, taking advantage of advances in data correction and processing and the experience gained in product generation and handling (section 8.1). This product should include improved radiometric calibration and correction for atmospheric water vapour absorption, improved Rayleigh scattering and ozone absorption corrections and corrections for scattering by stratospheric aerosols. Improved data navigation should be performed. Prior to any final decision to reprocess the G1KA data record, consideration should also be given to the correction of tropospheric aerosol effects, to the use of better temporal compositing procedures and to improved automated QA methods, since recent research advances indicate that these improvements can be implemented.

(3) Data acquisition and processing of the G1KA data record should be continued to ensure overlap of the record with forthcoming moderate-resolution sensors such as MODIS, GLI and MERIS. The overlap should be for at least 2 years in actual data records, and ideally there should be continuity with the planned NPOESS products. A minimum requirement must be to acquire and archive G1KA land data through to the NPOESS era. Global products should be available approximately 3 months after data acquisition.

9.2. *Recommendations to IGBP-DIS*

Recommendations to the IGBP-DIS regarding the G1KA land data are as follows.

(1) Work with the CEOS WGCV and other experts to ensure that reliable calibration and inter-calibration of the AVHRR sensors and follow-on instruments are carried out to ensure the creation of a reliable long-term record and that the resultant records are validated in relation to biospheric scientific priorities.

(2) Implement an on-going evaluation process that allows for the ready provision of critical science user feedback on the G1KA land data product.

(3) Ensure continued IGBP representation at AVHRR HRPT Ground Station Operators Meetings on a regular basis.

(4) Work with the Global (Climate, Ocean, Terrestrial) Observing Systems (G3OS) to ensure science requirements for the global land data record are documented and justified.

10. Conclusions

An initiative of IGBP-DIS, resulting in international collaboration with ground receiving stations world-wide and product generation and associated archiving and distribution infrastructures at EDC, has produced a G1KA land dataset based on standardized processing of NOAA AVHRR image data. To date, the dataset spans the periods 1 April 1992 to 30 September 1993 and 1 February 1995 to 31 December 1995.

The evaluation of the G1KA data product reported in this paper was an informal one involving volunteer experts and inputs from a limited number of users in the community. Nevertheless, it was possible to compare the implemented data product's characteristics with respect to the original specifications in some detail and assess the dataset's usefulness in selected research and applications. Future data product evaluations would benefit from a funded evaluation component and mechanisms to track users unobtrusively and obtain their feedback on an on-going basis.

The G1KA project has clearly been a success. The IGBP played a key role in defining the scientific requirements, and the G1KA data product, as implemented, matches the specifications of the IGBP-DIS and other affiliates very well and has exceeded them in some instances. CEOS played a critical role in the international co-ordination necessary to pull together the requisite AVHRR image data. In terms of implementation, a milestone dataset has been generated through the dedicated efforts of personnel at EDC. The G1KA product has been ordered by tens of thousands of users and is having a significant scientific impact. To date, the most notable global scientific contributions have been the derivation of global land-cover classifications and global fire products, although most uses are at the regional and local scales.

Reprocessing and continuation of the G1KA dataset to produce a long-term record for global change research are strongly recommended. The scientific drivers include the original scientific requirements as identified by the IGBP, the usefulness of detailed yet global land-cover mapping and characterization, the potential to monitor seasonal and interannual change and the creation of longer-term data records assisted by the overlap of data records and products between current and newer satellite systems.

Some of the identified problems with the dataset have been corrected by the data producer, whereas other deficiencies require more advanced processing to overcome them. Key improvements in the generation of future versions of the G1KA data product have been identified and prioritized, including updated radiometric calibration, more advanced atmospheric corrections and better navigation methods.

The G1KA dataset is an achievement that lays the ground-work for the continued generation of a global land data record at the 1-km scale using the NOAA AVHRR series and new sensors such as VGT, MODIS, GLI and NPOESS. Significant scientific contributions to global change research can be expected from such an on-going activity.

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Appendix: Acronym definitions

AATSR	Advanced Along-Track Scanning Radiometer (ESA)
ADEOS	Advanced Earth Observation Satellite (Japan)
AO	Announcement of Opportunity
ATSR	Along-Track Scanning Radiometer (ESA)
AVHRR	Advanced Very High Resolution Radiometer (NOAA)
BRDF	Bi-directional reflectance distribution function
CCRS	Canada Centre for Remote Sensing
CEOS	Committee on Earth Observation Satellites (international)

DAAC	Distributed Active Archive Center (EOS)
DAO	Data Assimilation Office (NASA)
DCW	Digital Chart of the World
DIS	Data and information system
DSL	Digital signal level
DTED	Digital terrain elevation data
EDC	EROS Data Center (USGS)
EOS	Earth Observing System (NASA)
EOSDIS	EOS Data and Information System (NASA)
ERS	European Remote Sensing satellite (ESA)
ESA	European Space Agency
FAO	Food and Agriculture Organisation (United Nations)
G1KA	Global 1-km AVHRR (dataset)
G3OS	Global (Climate, Ocean, Terrestrial) Observing Systems
GAC	Global Area Coverage (NOAA AVHRR data)
GLI	Global Imager (Japan)
GIMMS	Global Inventory, Modeling and Monitoring System (NASA)
GISS	Goddard Institute for Space Studies (NASA)
GOFC	Global Observation of Forest Cover
GSFC	Goddard Space Flight Center (NASA)
GVI	Global Vegetation Index (NOAA AVHRR product)
HRPT	High-Resolution Picture Transmission (NOAA AVHRR)
IGBP	International Geosphere-Biosphere Programme
IGOS	Integrated Global Observing Strategy (CEOS)
JRC	Joint Research Centre (European Commission, Ispra, Italy)
LAC	Local Area Coverage (NOAA AVHRR data)
LAI	Leaf area index
LCWG	Land Cover Working Group (IGBP-DIS)
LIDQA	Landsat Image Data Quality Assessment (NASA)
MERIS	Medium Resolution Imaging Spectrometer (ESA Envisat)
MISR	Multi-angle Imaging Spectroradiometer (EOS)
MODIS	Moderate Resolution Imaging Spectroradiometer (EOS)
MSS	Multispectral Scanner (Landsat sensor)
NASA	National Aeronautics and Space Administration (USA)
NDVI	Normalized difference vegetation index
NMC	National Meteorological Center (USA)
NOAA	National Oceanic and Atmospheric Administration (USA)
NPOESS	National Polar Orbiting Environmental Satellite System (NOAA)
NPP	Net primary productivity
PAL	Pathfinder AVHRR Land (NOAA/NASA dataset)
QA	Quality assurance
RMSE	Root-mean-square error
SeaWiFS	Sea-viewing Wide Field-of-view Sensor (USA)
SPOT	Système pour l'Observation de la Terre (France)
TM	Thematic Mapper (Landsat sensor)
TOMS	Total Ozone Mapping Spectrometer
USGS	United States Geological Survey (USA)
VGT	Vegetation (SPOT-4 sensor)
WGCV	Working Group on Calibration and Validation (CEOS)
WVS	World Vector Shoreline

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