GLOBAL CHANGE

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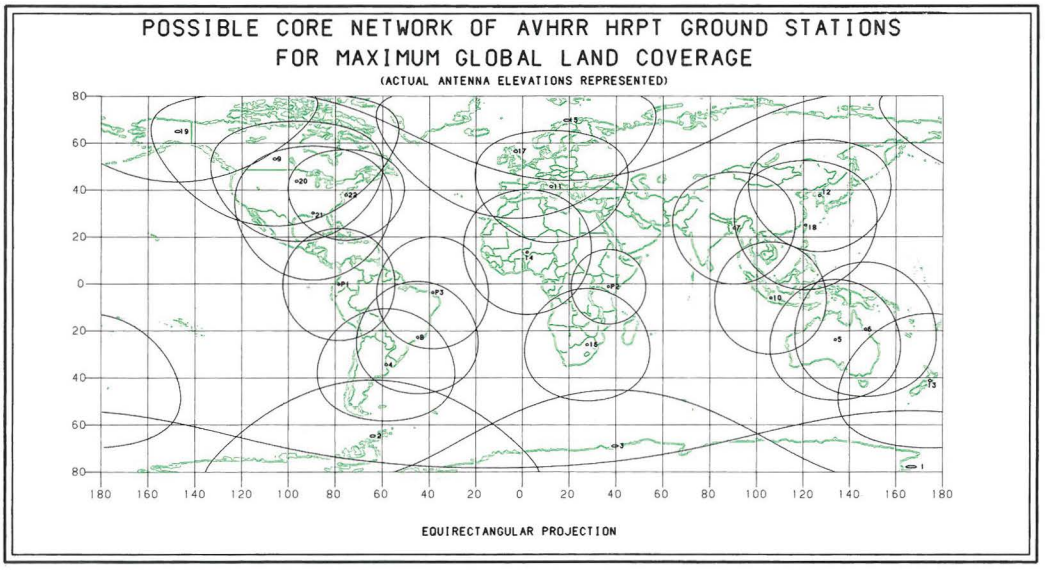
REPORT No. 20



Improved Global Data for Land Applications

The International Geosphere-Biosphere Programme: A Study of Global Change (IGBP)
of the International Council of Scientific Unions (ICSU)
Stockholm, 1992

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Improved Global Data for Land Applications

A Proposal for a New High Resolution Data Set

Report of the Land Cover Working Group of IGBP-DIS
Edited by John R. G. Townshend

The International Geosphere-Biosphere Programme: A Study of Global Change (IGBP)
of the International Council of Scientific Unions (ICSU)
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Preface

This report represents the outcome of a project of the Land Cover Working Group of the IGBP Data and Information System. It outlines a proposal to produce a global data set at a spatial resolution of 1 km derived from the Advanced Very High Resolution Radiometer primarily for land applications. The objective of the report is not to provide a detailed specification of such a data set, but instead is to outline characteristics of the data set to meet a number of requirements of the IGBP science programme and outline how it could be created. It is hoped that the report will form the basis for the production of the data set through the cooperative efforts of various international and national agencies.

A provisional version of this report was presented to participants of a joint IGBP-DIS and IGBP Core Project meeting in Toulouse, France in June 1991. The report received the broad endorsement of the meeting, and comments from participants of the meeting have been incorporated in this final report.

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Executive Summary

Introduction

1. Research into global change is rapidly rising in scientific priority. One especially important programme in this field is the International Geosphere-Biosphere Programme (IGBP), which is concerned with the biogeochemical aspects of the Earth system. The initial Core Projects of this programme are now defined (IGBP 1990), and research has been initiated or is in the planning stage for a wide range of proposed activities.

2. Two common requirements for IGBP projects are quantitative models to analyze the numerous complex interactions and feedbacks that occur within the earth system and large data sets containing geographically (or spatially) referenced data to parameterize and validate these models.

3. In the preparatory phase of the IGBP it became apparent that many of the required data sets either do not exist or only exist 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 is to ensure that data sets become available in a timely fashion and in a form appropriate for the fulfilment of IGBP's scientific objectives.

4. The role of the IGBP-DIS, at least in its early phases, is not to be directly involved in data processing and data set production, but is to take a proactive role in coordinating international activities to ensure that the necessary data sets are produced and made available. The present document represents the results of one such activity.

5. It is proposed that a global data set of the land surface is created from remotely sensed data from the Advanced Very High Resolution Radiometer to support a number of IGBP projects. This data set will have a spatial resolution of 1 km and will be generated at least once every 10 days for the entire globe.

Scientific requirements for a 1 km data set

6. Examination of the scientific priorities of IGBP reveals a requirement for global land data sets in several of the Core Projects and notably in the International Global Atmospheric Chemistry Project (IGAC), Biospheric Aspects of the Hydrologic Cycle (BAHC), Global Change and Terrestrial Ecosystems (GCTE) and Global Analysis Interpretation and Modelling (GAIM). These data sets need to be at several space and time scales and there will be a need to extrapolate between them. For example, global climate models typically have cell sizes of 250,000 km^2, whereas global models of hydrology and ecosystems are expected to require cell sizes at least as fine as 2,000 km^2. In order to parameterize these cells, much finer resolution data are normally required.

7. Examples of the need for information on land attributes include investigations of:

   (i) climate through the need for variables describing surface roughness, albedo, latent and sensible heat fluxes

   (ii) biogeochemical cycles and atmospheric chemistry, through such attributes as land cover conversion and the rate, distribution and type of biomass burning events

   (iii) water-energy-vegetation studies for which information on soil moisture, land transformations and evapotranspiration is required, amongst others.

8. Several surveys have revealed a dearth of global information for many attributes of the land surface. Such global data sets as do exist are largely derived from the piecemeal collation of diverse data sets, which leads to major problems of spatial and categorical consistency. Because of such problems, remote sensing from space is increasingly regarded as an essential source of data especially for those attributes requiring global or regional coverage and regular monitoring or updates.

9. Extracting information for land applications from remotely sensed data 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 variables may be attempted through either statistical methods or explicit inversion techniques.

Types and uses of AVHRR data

10. Although many types of remotely sensed data of the Earth's surface have been collected during the past two decades, data from the Advanced Very High Resolution Radiometer (AVHRR) of NOAA have been used most frequently for global land studies. This is because its spectral bands are reasonably well suited to the detection of important terrestrial attributes, especially those relating to vegetation. But most importantly it provides data with a high enough temporal frequency that global data sets can be compiled in which cloud cover is substantially reduced. Hence regular monitoring of almost the entire global land surface becomes feasible. The AVHRR has significant limitations especially relating to calibration, but international efforts are being made to ameliorate this particular problem.

11. 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, green leaf biomass, net primary productivity, and photosynthetic capacity. Estimates of evapotranspiration have been made as well as surface temperature and the distribution and areal extent 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.

12. One of the largest problems relating to the data from the AVHRR is their availability. Although the whole global land surface is sensed on a regular basis, global data sets at the basic sensed resolution of 1.1 km 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 nadir resolution of 4 km. Even these data are not currently available in a form suitable for use at a global scale for land applications.

13. Currently the availability of AVHRR data is limited to the following:

(i) The Global Vegetation Index (GVI) data set is regularly created by NOAA with a spatial resolution of 15-20 km. This data set has been a most important spur to the use of global data sets, but it is now recognized that it has a number of significant limitations. Revised, improved forms of these data will shortly be available.

(ii) A NASA data product from the Goddard Space Flight Center based on the GAC data product is being generated with a spatial resolution of about 8 km, produced on a continent by continent basis. However, it has not yet been produced on a globally uniform basis. Related efforts are underway at the European Community's Joint Research Center, Ispra.

(iii) Local 1 km archives of varying spatial extent and length of historical record are available, such as through the NOAA LAC archive and from various national and regional reception facilities. Areas for which data sets are most readily accessible include the North American continent (from the USGS EROS Data Center and the Canada Center for Remote Sensing), and Europe and north-west Africa (through ESA and some European research groups).

14. Future important efforts in generating global data sets include :

(i) the joint Pathfinder activity of NASA and NOAA, which will lead in the next few years to a complete retrospective AVHRR data set from 1981 onwards at a spatial resolution of 9 km and a frequency of once every 10 days;

(ii) data from various new sensors, the most important of which are likely to be the Along Track Scanning Radiometer, particularly the version to be placed on the European ERS-2 from 1994 onwards, with a spatial resolution of 1 km though with a lower temporal frequency than the AVHRR, and the new sensors of the Earth Observing System, notably the US Moderate Resolution Imaging Spectrometer (MODIS) and the European Medium Resolution Imaging Spectrometer (MERIS).

15. There are no current plans for the creation of regular global data sets at spatial resolutions finer than those described, but it is apparent that for several IGBP activities a spatial resolution of 8 km or coarser will be insufficient for their needs. Given the fact that data with a nadir resolution of 1.1 km are obtainable for the whole land surface of the earth, it is appropriate to explore the possibility of compiling such a data set.

Required characteristics of a global 1 km data set

16. Data should be provided to users in a form which minimizes pre-processing by users. The global 1 km data set should contain:

(i) radiometrically corrected radiances for all five channels (see paras. 24 - 28)

(ii) the normalized vegetation index derived from the corrected radiance

(iii) the date as well as sun and look angles for each pixel selected.

These data sets should be well registered to an equal area global coordinate system.

17. High repetivity of data improves the chances of acquiring a cloud-free view of every location within a finite time period. Because of the high cloud cover in many parts of the world, it is necessary to plan for the collection of data from every orbit. These data will then need to be composited to form synthetic products relating to minimum time periods as long as 10 days for global coverage, though at higher latitudes the frequency could be increased to once every 5 days. Composite data sets in which cloud is sufficiently removed for many applications may have to be generated for periods as long as 30 days and in some humid tropical regions large amounts of cloud may still remain.

18. Multi-temporal global coverage of data, achieved through a mixture of recorded data and data from ground receiving stations, is required, though there may have to be some pragmatic concentration on priority areas.

19. The minimum length of record should be a year, and ideally a system should be put in place which leads to the continuous acquisition of 1 km data to provide a base line data set prior to EOS towards the end of the decade.

Pre-processing procedures

20. Substantial effort will be required in the pre-processing of the data set to make it suitable for the extraction of information. It is essential that a set of procedures is established, for which there is general agreement from the IGBP community.

The main stages in preprocessing are radiometric calibration, atmospheric correction, geometric correction and temporal compositing.

21. In terms of radiometric correction, AVHRR data from bands 1 and 2 pose particular problems because of the absence of on-board calibration. Calibration is essential because of drift of instruments and differences between the AVHRR sensors.Hence several groups are involved in attempts at vicarious calibration. International coordination, possibly through IGBP-DIS, with a regular means of communicating information to update calibration coefficients needs to be established. The 1 km data set should use the best available ancillary data to improve the usefulness of the data for long term investigations.

22. For some aspects of atmospheric correction, procedures are reasonably well established, as in the case of the Rayleigh scattering and ozone corrections. But for water vapour and aerosols there is no general agreement on common methods and soon a decision will have to be made on whether or not to apply one of the available methods. Close liaison with the NASA/NOAA Pathfinder activity is recommended since this group is also actively considering and carrying out research into these matters.

23. Data need to be corrected geometrically so that uniform fields of well registered data are created using an equal area projection.

24. Several aspects of pre-processing still require additional research to optimize procedures. For example, better procedures for compositing images (see para. 17) need to be developed to minimize cloud effects for both the individual channels and the vegetation index.

Availability of current AVHRR 1 km data

25. Data recorded on board the NOAA platform are known as Local Area Coverage (LAC). Images of a substantial proportion of the Earth's surface can be acquired through this means, but global coverage cannot be achieved. Also, priorities other than scientific requirements mean that data are often not collected in a manner to optimize global data collection.

26. A comprehensive review of the numerous AVHRR ground receiving stations shows that data from virtually the entire globe can in principle be acquired. The main gaps in coverage are in south-west Asia and northern Siberia.

27. Ensuring that data from ground stations regularly and reliably supplement the LAC data will require international coordination. Preliminary discussions between space agencies have already started to assess the feasibility of such a plan.

28. A global facility will be required to ensure the creation of a uniform data set, which is made readily available to the whole IGBP community.

Data management

29. It is recommended that information on the availability of the 1 km data set and other data sets relevant to IGBP activities is made through the IGBP Directory, which will be based on the NASA Master Directory.

30. Long term archiving needs to be established and it is recommended that this could be carried out within the framework of the ICSU World Data Center system.

31. A review of the available media for the data set suggests that CD-ROMs may be the most suitable for distribution purposes.

32. Consideration of the various issues raised in defining the AVHRR 1 km data set raises a number of generic issues relating to data management:

    (i) The relationships between IGBP-DIS and various other activities such as the EOS-DIS, the World Data Center system and the Global Climate Observing System need to be established.

    (ii) Mechanisms need to be established with key space agencies and major data suppliers such as the USGS in order to ensure that IGBP user requirements are properly represented through IGBP-DIS, so that AVHRR and other remote sensing data sets can properly support IGBP activities.

    (iii) The relative roles of Core Projects and IGBP-DIS in data management need to be established through consultations between these groups, and in particular through the mechanism of the IGBP-DIS Standing Committee.

1. Scientific Requirements for 1 km Data

1.1 Global Change Research

An international global change research strategy has been articulated in a number of recent documents (e.g., IGBP 1990, Houghton *et al.* 1990, NAS 1990, NASA 1987). It is becoming increasingly evident that the emerging discipline of earth system science is both multi-disciplinary and broad in scope. Nonetheless, the essential elements can be examined from the perspective of the physical and biological processes which influence global biogeochemical cycles and climate. The IGBP has a major role in developing an understanding of the biogeochemical aspects of this Earth system.

Global change research has two important, basic requirements. First, because the Earth system is complicated by multiple interactions and feedbacks, numerical models are required. To incorporate processes operating at different temporal and spatial scales, these models need to be scaled hierarchically from a suite of nested models, measurements and observations. Second, a large amount of geographically-referenced data will be needed to parameterize these models. A variety of data sets spanning several levels of spatial and temporal resolution will need to be developed, checked for consistency and accuracy and made available to various global change research projects. The development of data must be done in tandem with, and in the context of, the scientific questions being posed and the needs of the models or analyses being developed.

The availability of data and how they will be managed are two critical facets of future global change research. Global science is data-limited, and therefore new efforts must be engaged which foster the development and validation of global data sets. Questions arise as to which data sets are needed, what are the appropriate spatial and temporal scales for each data set, how will they be developed so as to suit the needs of the maximum number of users, on what basis they will they be validated, and how their availability can be insured for long-term analyses.

It is prudent to begin with a small number of test data sets, which are at once currently needed and general enough to satisfy the needs of many different scientific questions. One such data set is global scale land cover. Land cover data are required by most of the IGBP Core Projects and are a critical, but missing, element in models of global ecosystems and hydrology. In principle, land cover data can be obtained from space-based platforms. However the issues surrounding the acquisition, processing, and organization of these data are complex and require a dedicated effort by the international community.

1.2 Data for Global Change Research

The requirements of the IGBP community for data sets are extremely varied, but there are a number of common issues that have to be considered.

1.2.1 Types of Data for Global Change Research

Two basic types of data for global change research can be distinguished. The first consists of data for documenting and monitoring global change.

These data sets include, for instance, global land and sea surface temperatures and atmospheric concentrations of carbon dioxide and other trace gases. The second consists of data which characterize important forcing functions; these data are required to parameterize models and develop a predictive understanding of global-scale processes.

Both of these objectives are non-trivial. For instance, the change in land surface temperature needs to be derived with relative precision (± 0.5° C) if one is to document secular trends in the global temperature. Data required to parameterize models must be acquired at the appropriate spatial and temporal scale, and the measurement units must mesh well with the parametrization scheme being employed. For instance, the Normalized Difference Vegetation Index (NDVI; Justice *et al.* 1985, Tarpley *et al.* 1984, Townshend and Tucker 1984) can be derived from polar orbiting satellites to form the basis of important global land cover data sets so long as the index can be transformed into meaningful physical terms. These data are available from 1981 and hence have the potential to provide consistent long term measurements.

Related to both these types of data are other data sets required for modelling and monitoring the impacts of global change on natural and human systems. Of crucial importance to global change research is that all of the data sets must be capable of providing consistent, long-term measurements or observations (Rasool 1987). In the present document the emphasis is on land characteristics, since these are the properties where it is believed there are currently the most important deficiencies in terms of global data sets.

1.2.2 *Geographically-Referenced Data*

The spatial nature of global change research demands geographically-referenced data sets, which form an essential basis to enable field measurements to be extrapolated to regional estimates. For instance, *in situ* measurements in different landscape units can be extended to a larger area-mosaic composed of these individual units. The spatial domain of data also provides constraints on integrated source-sink model analyses. The work of Tans *et al.* (1990) provides an example of the need for spatially defined data at the global scale. In this analysis geographically-referenced source terms of carbon dioxide fluxes from biomass burning and fossil fuel combustion were combined with maps of ocean pCO_2 distributions and the meridional gradient of atmospheric CO_2 concentration in a 3-D tracer model to constrain geographic source and sink terms.

One of the problems with past use of point, tabular and cartographic global data sets is the inadequacy of spatial extrapolation. For many purposes global data sets are needed which are capable of providing comprehensive detailed geographically referenced observations within a regular tessellation.

1.2.3 *Data Across Scales*

Data may represent areas from meters to hundreds of kilometres and time periods from hours to years. Landscapes are inherently spatially heterogeneous, but their heterogeneity varies with scale. The scale at which a landscape feature is represented is a critical factor in any analysis, and has become an important issue for global change studies (Rosswall *et al.* 1988). While some questions can validly be posed at coarse scales, some fine scale features, such as wetlands or fires, have important influences on regional or global processes.

No single scale will satisfy all the requirements of IGBP Core Projects. The general consensus is that most global studies will require extrapolation across many scales.

General circulation and global climate models are developed on coarse grids of 1-40 x 10^4 km^2. In contrast, hydrology and ecosystem models are developed at grid scales of 2 - 3 x 10^3 km^2. Moreover, data from *in situ* measurements are made at scales much finer than this. It is unlikely that a single, completely integrated model can be developed which could be utilized at all scales. Instead, layered models which utilize data at appropriate scales for analysis will provide inputs to other models in a hierarchical approach. These considerations lead to the significant conclusion that data sets must be developed hierarchically.

1.2.4 *The Opportunity for Remote Sensing Data*

A number of planning efforts have already made general statements on the need for, and approach to building global databases for global science (NASA 1987, Mounsey and Tomlinson 1988, NAS 1990). It is clear that many existing data sets, especially for land applications, have been derived from cartographic or tabular sources. Compilations of data sets from such sources are fraught with problems (see Section 1.3). The fact that variables are required in uniform geographic and temporal dimensions suggests the use of satellite remote sensing as the major new source. Satellites have been shown to be a useful source for a variety of needed data (Rasool 1987). But there have been but a few efforts to compile global data sets from remote sensing sources for the global change scientific community.

The required characteristics of data sets to analyze global change point to the clear value of remotely sensed data. Many of these data have the potential to be obtainable globally and can be used to derive a number of important monitoring and modelling parameters. Already many remotely sensed data have been acquired for several years allowing the creation of long term data sets, and their continued collection will make the monitoring and modelling of global change more reliable. These tasks need to be achieved at a variety of spatial scales, and this can be realized by using an appropriate suite of sensors and carefully designed data and information systems to generate higher level products. Thus a variety of important variables can be obtained globally, in the form of data sets which are multi-temporal, geographically referenced and which have a multi-scale hierarchical form.

Data describing land cover are required globally in many research analyses and modelling studies. Many of these data can be estimated from space-based observations at various scales, and can be obtained on a multi-temporal basis globally. However, to date there is no validated higher level product depicting land cover, which has been derived from remote sensing and which is available at a global scale

1.3 Production and Use of Land Cover Strata

Obtaining information on land characteristics from remotely sensed data has been achieved in two basic ways.

In the first approach, described in this section, areas are stratified into categories or classes.and then ranges of values of biophysical characteristics are assigned to each of them. In the second approach, these characteristics are estimated either statistically or by direct inversion using the remotely sensed data (Section 1.4).

1.3.1 *Currently Available Land Cover Data Sets*

Few land cover data sets are available in digital form for the entire globe. Those which exist have been derived from cartographic sources at very coarse scales. Some of the earliest formulations were developed to support general circulation and atmospheric tracer models (e.g., Matthews 1983, Henderson-Sellers *et al.* 1986). The purpose of these data sets has been to delineate broad ecosystem classes around the globe as a means to define surface roughness, albedo, and other physical feature mediated by vegetation. These data have also provided a means to estimate global distributions of primary productivity and water/energy balance. The formulation by Matthews (1983) is probably the most often utilized data set. This grid-cell data set was derived by combining approximately 100 individual map sources into a single, UNESCO-based scheme of vegetation classification. The major vegetation type is defined for each 1° x 1° land surface grid cell equivalent to a horizontal resolution of approximately 110 km at the equator.

Other digital data sets have been developed to support global ecosystem models, particularly for model analyses of the global carbon cycle. A ½° by ½° degree grid cell map (50 km horizontal resolution) has been developed of vegetation types and associated carbon contents (Olson *et al.* 1983).

Like the Matthews map, this data set delineates both natural and disturbed land uses. Researchers at the University of New Hampshire, USA, have prepared a digital data set of actual and natural land cover in vector form at a horizontal resolution of approximately 10 km. It differs from the previous data sets in its finer resolution, somewhat comparable to AVHRR-GAC, and its delineation of pre-disturbance vegetation (Skole *et al.* 1992).

A third type of digital data set has been developed based on climatological variables. A ½° x ½° grid cell map has been developed of Holdridge Life Zones of the world, an eco-regionalization scheme based on temperature, precipitation, and evapotranspiration (Emanuel *et al.* 1985). Since the categories are climate-sensitive, the data set has been used to make first order projections of vegetation distributions under a 2 x CO_2 scenario.

These digital data sets are currently the best available sources of global vegetation maps. The fact that they define vegetation type using some pre-defined nomenclature has advantages both in allowing assignments of parameters, such as carbon or biomass, to categories understood by ecologists, and also in conveying a general sense of structure and function, in terms familiar to ecologists. Nonetheless, all of the data sets suffer certain critical problems:

- the nomenclature itself usually varies from one data set to the next, and means different things to different scientists
- type-classifications require a modeler to make somewhat arbitrary parametrization assignments, usually from point measurements found scattered in the literature
- the complete data set may be derived from individual primary sources, each using different systems of nomenclature and each from different dates
- production of the data set involves interpretation, generalization, or abstraction, of vegetation and vegetation boundaries, and thus does not necessarily portray actual distributions
- most existing data sets have very coarse resolutions (50 - 100 km)
- none of the existing data sets provide indications of phenology or other intra-annual variations

- all are static generalizations, incapable of providing indications of inter-annual changes.

Clearly, existing sources have proven to be useful first order delineations of land cover, and these will probably be useful for a few years to come. The unreliability of global estimates of land cover from such sources can be demonstrated when comparisons between different efforts are made (Townshend *et al.* 1991). The very high variability between estimates made a short time apart clearly illustrates their failings (Fig. 1.1).

The shortcomings of these cartographic approaches suggests the strong need to develop land cover data sets derived from remotely sensed data. In the next section we review generally the scientific justification for land cover data in three areas of global change research: climate studies, global biogeochemistry, and interactions between water, vegetation and energy.

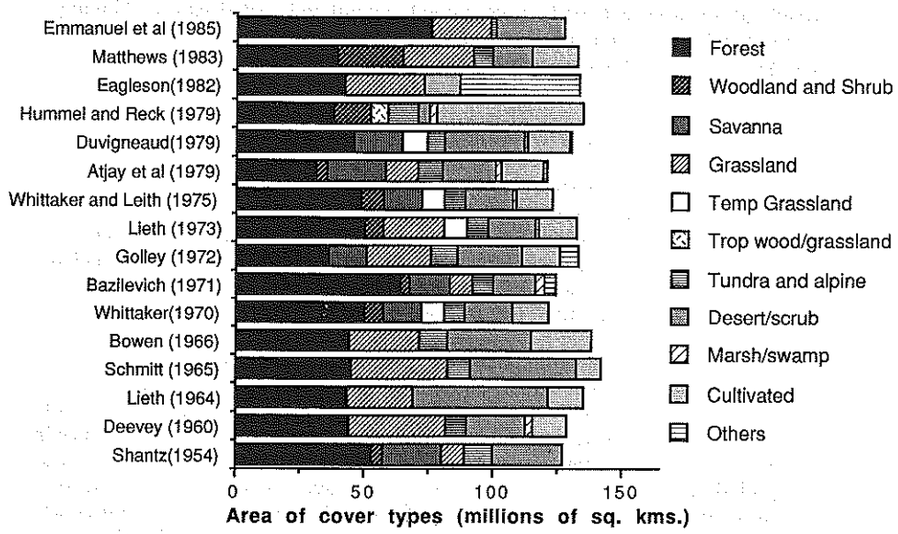


Fig. 1.1 Variations in estimates of global land cover classes based on conventional collations of cartographic sources (for references see Townshend *et al.* 1991). Differences in the total cover relate to the inclusion or exclusion of categories such as ice fields and deserts.

1.3.2 *Land Cover Data for Climate Studies*

To a large degree land cover determines factors such as surface roughness, albedo and sensible and latent heat flux. These factors are increasingly important variables in general circulation models (GCMs) (e.g., Sellers *et al.* 1986, Sato *et al.* 1989, Sud *et al.* 1990). These models use coarse grids, typically with a 200 km or even coarser horizontal resolution. This coarse resolution is justifiable, because of rapid mixing in the boundary layer, and hence fine scale data are presumably not required and a general distribution of land cover is probably sufficient. Nonetheless, the aggregate sum of various boundary layer transfers for each coarse grid is dependent on a sub-grid parametrization.

Land cover has a major effect on sensible heat flux, since it influences global albedo and surface roughness for parametrization of atmospheric drag. These inputs, however, are probably required at coarse scales with horizontal resolution typically of 200 km.

Latent heat flux is mediated by evapotranspiration. Actual evapotranspiration (AET) is in turn a function of land cover type, soil moisture, and climatology (e.g., temperature). Land cover directly provides information on AET, since vegetation mediates water balance. The way water is used varies geographically with different ecosystems as a function of whole plant and xylem water potentials, leaf area and stomatal closure, rooting depth, and canopy structure across the soil-plant-atmosphere continuum. Moreover, seasonal variations within ecosystems influence patterns of latent heat flux throughout the year.

For these purposes, geographically-referenced land cover data sets, which include a measure of seasonality, are important for climate modelling beyond their simple utilization as a means to parameterize sensible heat flux (see Section 1.4). Latent heat flux is controlled to a large degree by water balance relationships within plants. Physiologically mediated processes, such as evapotranspiration, determine the surface boundary conditions of important GCM parameters such as stomatal resistance. However, these plant physiological processes operate at very fine temporal and spatial scales. Although GCMs are ultimately parameterized at coarse scales, the scale appropriate for estimating vegetation dynamics will be more resolved than the GCM grid.

1.3.3 *Land Cover Data for Biogeochemical Cycles and Atmospheric Chemistry*

Land cover and land cover conversion data are important for determining the biogeochemical cycling of carbon, nitrogen, and other elements at regional to global scales. There has been much recent work with global terrestrial carbon models (Houghton and Skole 1990, Houghton *et al.* 1991, Houghton *et al.* 1987, Moore *et al.* 1981). These analyses suggest that the contribution of carbon to the annual increase in atmospheric carbon from land cover conversion is large, and of the order of 1-2 x 10^{15} g C yr^{-1}.

The estimates of carbon released from land clearing and biomass burning combined with the estimates of oceanic uptake of carbon cannot now be reconciled in a balanced global budget. The biotic and oceanic estimates are either incorrect or incomplete. Recent work has used geographically detailed estimates of carbon emissions and ocean uptake rates in conjunction with a 3-D atmospheric tracer model which suggest that terrestrial vegetation in mid to high latitudes might be a net sink (Tans *et al.* 1990). Increased net production in undisturbed systems might be a possible causes of this sink; however, the magnitude of proposed net carbon flux in relation to gross exchanges is too small (around 1%) to measure directly in the field. Changes in land-use may also be involved, with the possibility that the effects of agricultural abandonment have been under-estimated (Houghton and Skole 1990, Melillo *et al.* 1988), but there have been few detailed studies of land cover conversion or reversion in mid to high latitudes. Uncertainties also exist in relation to nutrient interactions, notably of nitrogen and carbon (Melillo and Gosz 1983) and their impacts on productivity (Abel 1989, Melillo *et al.* 1989).

All these uncertainties, and the research questions which they pose, show the need for detailed land cover and land cover change data. To improve estimates of the global net flux of carbon due to land use change, models require refined estimates of two important variables: land cover conversion data and biomass. It has been suggested that biomass can be derived globally from empirical relationships, based on work carried out in South-east Asia (Brown *et al.* 1991). Proposals have also been made to derive global biomass using dynamic element cycling models (Raich *et al.* 1991). The dynamics of net ecosystem production and nutrient interactions present complex problems involving relationships between the physical environment, climate, and ecosystem patterns of nutrient use and

partitioning. For these kinds of models, functional land cover classifications would play an important role. A functional classification is one which defines vegetation by characteristics such as nutrient cycling (involving nitrogen mineralization rates) or productivity (as in net primary productivity NPP), rather than by physiognomic characteristics. The conventional land cover map is likely to be of less value in this regard than a dynamic delineation acquired from satellites.

Land cover data are also integral to analyses of trace gas dynamics. Natural ecosystems determine the dynamics of many important species such as CH_4 and N_2O and the conversion of ecosystems results in changes in trace gas dynamics. For example, conversion of tropical forest to pasture can be an important factor in trace gas dynamics for several years after pasture formation (Luizão *et al.* 1989, Matson *et al.* 1987, Goreau and de Mello 1988). Land conversion in the tropics is often associated with biomass burning, which may be an important source of CH_4, CO and other radiatively important trace gases. Uncertainty in current estimates of trace gas dynamics results from the lack of data on the rate and distribution of biomass burning events, the type and condition of the biomass and emission factors of trace gases. Detailed land cover assessments from satellites can contribute in the provision of all these data.

1.3.4 *Land and Cover Data for Water-Energy-Vegetation Studies*

The IGBP Core Project on Biospheric Aspects of the Hydrological Cycle (BAHC) is directed at improving our understanding of the biological factors affecting the hydrological cycle (IGBP 1990). A wide range of data is required for these studies, and of particular importance are land cover data sets. A number of reports have outlined the research priorities for global change research in this field (e.g. IGBP 1990, Bolle 1991, Becker *et al.* 1988) and an overview of the data requirements in this area of research has recently been provided by the U.S. National Research Council (NAS 1990). The proposed approach is hierarchical, where data from ground measurements and field campaigns are integrated with meso-scale measurements and global models, through the parametrization of a suite of multi-level series of models (Fig. 1.2).

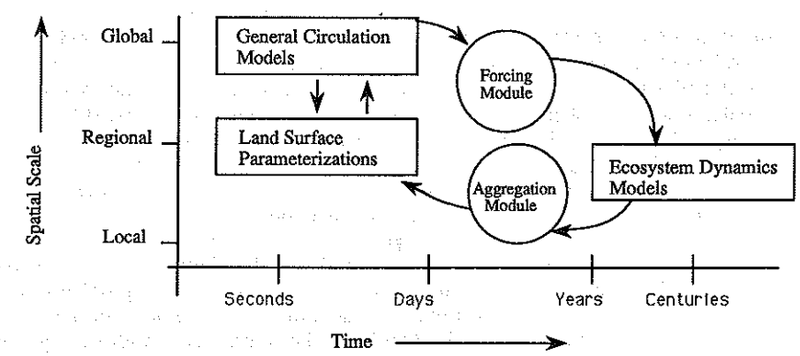


Fig. 1.2 Time and space scale relationships between models and their parameterizations (NAS 1990).

For these studies the required global data sets include land transformation, topography, vegetation, vegetational functions, soils and soil moisture, meteorology and hydrology. Vegetation function data are primarily linked to seasonality (phenology), so that the timing and amount of water released through the land surface boundary can be quantified. This will require the use of large-area data sets of spectral vegetation indices. Also it will be critically important to provide global land transformation data. Thus the data obtained must be able to portray inter- and intra-annual dynamics at the scales appropriate for their detection. As will be discussed in the next section, these required spatial and temporal scales will demand the use of satellite data sets.

1.4. Direct Estimation of Land Characteristics.

The approach described in the previous sections is to use reliable sets of land cover data in order to estimate a wide range of biophysical characteristics on the basis that specific land cover types possess a relatively narrow range of values of these characteristics.

An alternative approach is to attempt to estimate various characteristics of the land surface directly from remotely sensed data along with other ancillary data sources. This involves a double inversion. Firstly the remotely sensed data themselves have to be converted to surface radiation measures such as radiance, reflectance or brightness temperature, involving procedures such as atmospheric correction and calibration. Secondly, these corrected data have to be converted to biophysical properties of the land surface.

There is a need for information on numerous properties and the procedures for estimating them can have varying levels of complexity. For example, if brightness temperature is to be converted into a useful thermodynamic temperature, several factors may need to be considered including emissivity, which is itself spectrally dependent. The presence of mixtures of soils and vegetation in the same field of view with different emissivities, the relation between the instantaneous satellite measurement and diurnal variability, the influence of terrain variability and various directional dependencies of the data also need to be addressed.

The following description of some of the key properties, required by the global science community and for which remote sensing can make a contribution, is based on Bolle (1991):

i) *Vegetation index.* Spectral vegetation indices derived from near infrared and red spectral bands are intermediate properties which enable various plant canopy characteristics to be estimated. These include leaf area index and photosynthetic capacity, and when integrated over a growing season they can be related to net primary productivity. However, there is considerable evidence that these relationships are canopy-type dependent, so that independent information on the type of vegetation being imaged improves the estimates. Estimates of the seasonality of canopy characteristics can also be made.

ii) *Albedo.* Knowledge of albedo can be used to estimate the photosynthetically active radiation and the solar net flux at the surface. One of the principal problems in estimating albedo is relating measurements made in limited segments of the spectrum to the complete band width that has to be considered. Additionally terrain can have a major influence in more rugged areas, and there is a need to take account of slope directions and altitude.

iii) *Solar radiation flux at the surface.* Specific broad band Earth radiation budget sensing systems will provide the most reliable spectrally integrated information overall but geostationary satellite sensors and AVHRR data can also contribute, the former providing more frequent data and the latter more precise spatial information. International Satellite Cloud Climatology Project (ISCCP) products currently only provide information at a spatial resolution of 250 km.

iv) *Evapotranspiration.* Three basic approaches can be identified to estimate evapotranspiration: (a) from the energy budget equation in which the Bowen equation is used; (b) by application of atmospheric boundary layer models; or (c) by closing the mass budget. Information from the vegetation index can be used to estimate stomatal resistances. Operational estimates of evapotranspiration may also require information about vegetation and soil types and estimates of wind speeds.

v) *Surface Temperature* As discussed, estimating land surface temperature from remote sensing is a complex question. The considerable importance of this variable for calculating energy balance components and evapotranspiration has lead to considerable research efforts to estimate it more accurately and is the subject of an IGBP-DIS Working Group chaired by Professor F. Becker of the Université de Strasbourg. Surface temperature measurement is also of high significance in monitoring fires, the temperature of the fire being an important factor controlling the character of combustion products.

Other important global properties required for the IGBP include net radiation flux, precipitation, soil moisture, and surface roughness. Estimating the latter two characteristics will almost certainly be dependent on the use of various types of microwave satellite data. With the continuing development of the IGBP Core Projects, many other important properties will undoubtedly be progressively identified for which global coverage is required. For all these biophysical attributes it will be necessary to determine how they can be estimated with appropriate spatial resolutions and temporal frequencies. Specifically the following questions will need to be addressed by the various scientific communities involved in the IGBP:

(i) What properties have to be measured or estimated in order to carry out the objectives of the IGBP?

(ii) What are the precision and accuracy with which the measurements and estimates have to be made?

(iii) What are the time frequencies and spatial resolutions of the information required for these objectives?

(iv) To what extent can remotely sensing and other procedures provide data in order to match the requirements described in stages (i), (ii), and (iii)?

(v) When a good match cannot be found, can new procedures and methods be devised to produce an acceptable approximation to the requirements?

Work of the International Satellite Land Surface Climatology Project (ISLSCP) has done much to contribute to current understanding of how ground properties can be derived quantitatively from satellite measurements. This work has involved a series of very intensive field experiments in several parts of the world (e.g., Rasool and Bolle 1984, Becker *et al.* 1988, Sellers *et al.* 1988).

1.5 Remote Sensing of Land Cover Characteristics: A Hierarchial Approach

Land cover data have been identified by a number of national and international coordinating committees as essential data for nearly all facets of global change research (IGBP 1990, NAS 1990). Land cover data are particularly important for three established IGBP Core Projects: The International Global Atmospheric Chemistry Project (IGAC), Biospheric Aspects of the Hydrological Cycle (BAHC) and Global Change and Terrestrial Ecosystems (GCTE).

Scale is emerging as a critical issue. Each of these projects will be built upon a framework of multi-level data, covering various temporal and spatial scales. Global integration of these separate projects will require an understanding of the nature and importance of scale. Comprehensive provision of data suitable for these IGBP projects will require an organized, hierarchical land cover data set. Figure 1.3 diagrammatically shows the various levels of model development and implementation for global change vegetation studies. The spatial and temporal resolution of global biogeochemistry models are the most coarse of the various models shown in the figure, yet they remain finer in scale than GCMs.

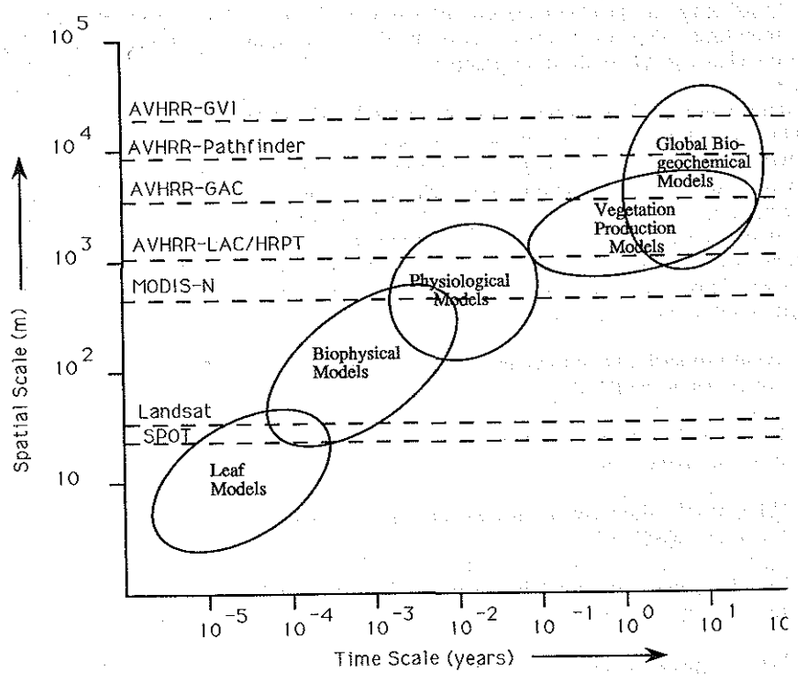


Fig. 1.3 Space and time scales models for global vegetation studies in relation to information provision by remotely sensed systems. (GVI, Global Vegetation Index product; GAC, Global Area Coverage product; LAC/HRPT, data with a 1.1 km resolution either through Local Area Coverage recorded on board the satellite, or through High Resolution Picture Transmission direct to ground receiving stations. See Section 2.3 for more details).

Most vegetation studies will require land cover data at scales much finer than GCMs. Not all data requirements are determined by the scale of the GCM. Figure 1.3 shows that vegetation models will need to be developed across a range of scales. The type of satellite data utilized will be determined by the scales of the application.

The scale hierarchy concept can be more fully illustrated in studies of trace gases, where extrapolation of fluxes will be developed for 10 km x 10 km study sites (IGBP 1990). IGBP hydrological studies propose to scale up from 1 x 1 km SVAT models to 10 x 10 km integrated SVAT model arrays, to 100 x 100 km mesoscale models (IGBP 1990).

There is an emerging view regarding the appropriate scale for analyzing land cover and land cover conversion. The suitability of 4 - 8 km GAC data for delineating broad land cover types and phenology has been demonstrated (Malingreau 1986, Malingreau and Tucker 1987). The utility of 8 - 15 km data for land cover classification and phenology has also been shown by a number of authors (e.g., Justice *et al.* 1985 and Tucker *et al.* 1985), but it is too coarse for monitoring land cover conversion and reliable detection of land transformation requires resolutions of 1 km or finer (Townshend and Justice 1988). This observation is supported by detailed analyses of tropical deforestation, which suggests that even 1 km data might be too coarse for quantifying the area and rate of deforestation in some regions (C. J. Tucker pers. comm.), although a 1 km data set would assist stratified sampling.

Moreover, as noted previously the scale required for GCMs is not necessarily the requisite scale for all IGBP studies. Even for the coarsest scale vegetation analysis, which operate at resolutions of about 200 km, the data sets required could be vastly improved if there were sub-grid cell information, since the dominant vegetation type does not provide all the required information. Some landscape features are local in scale but are critically important for global change studies. Examples of such landscape features are: the flux of trace gases in northern bog systems; the extent of flood plains and flooded forests; the distribution of fires and biomass burning; ecosystem transition gradients and boundaries; and land cover conversion and deforestation.

The sort of hierarchical approach which needs to be adopted is summarised in Table 1.1. Inevitably the levels in this hierarchy partly relate to scientific requirements and partly to pragmatic considerations of what remotely sensed data have been collected.

Table 1.1 A hierarchical approach for land cover data sets

Level of Hierarchy	Time Frame	Spatial Resolution	Temporal Resolution	Data Source*
H1	1-2 years	~ 20 km global	monthly	GVI
H2	2 years	~ 8 km global	weekly	GAC
H3	5 years	~ 1-2 km global	weekly	LAC/HRPT
H4	1-2 years	20 m - 1 km local/regional	variable	SPOT/Landsat, LAC, etc

* See Fig 1.3 for explanation of abbreviations and Section 2.3 for further details

An indication is also given in this table of the various data sources which are most suitable for the different levels. A discussion of the characteristics of these data sets is provided in Section 2.

The most notable omission in these data sets is global 1 km data. As an illustration of the benefits of this finer resolution data set compared with existing and planned coarser resolution data sets, consider Fig. 1.4, which shows the relationship between changes in the NDVI and spatial resolution (Townshend *et al.* 1991). Specifically note that with the exception of the test area from Rondonia, the curves are relatively steep between 10 km and 1 km indicating the significant benefits of a finer resolution data set.

It should also be noted that there is a lack of coordination in the provision of either wall-to-wall data with high spatial resolution from Landsat or SPOT or even well sampled data in space and time. Consequently an effort will also be needed to develop high resolution (20 - 80 m) data sets for studies of land cover conversion. This topic is outside of the scope of the present document, but urgently needs to be addressed.

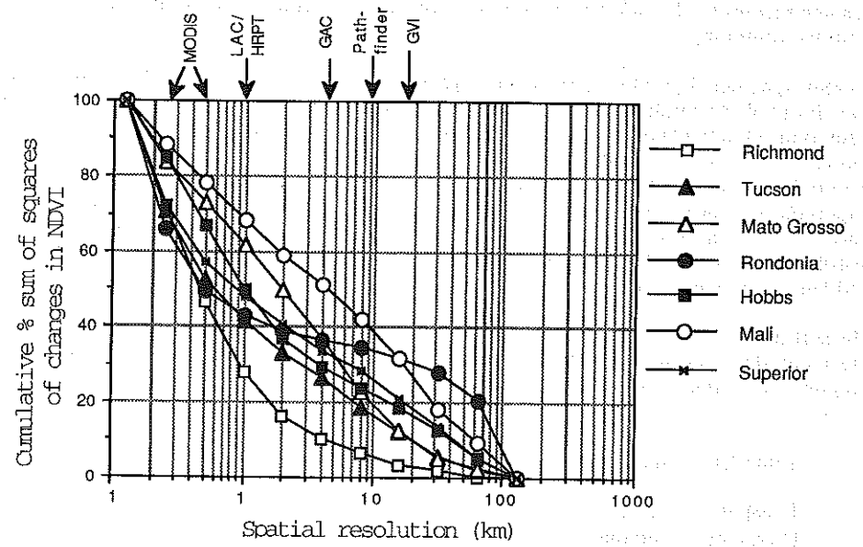


Fig. 1.4 Cumulative frequency plots changes in the NDVI with spatial scale (Townshend *et al.* 1991).

1.6 Conclusions

The previous account has demonstrated the need for information on land surface state and processes at a wide variety scales in order to satisfy the requirements of many aspects of the IGBP Core Projects.

There are various approaches in obtaining such data. One approach, which has received considerable attention of late, consists essentially of deriving information about land cover

state, and then estimating or at least constraining the estimation of a wide variety of biophysical properties (Section 1.3). A second approach is to attempt to estimate biophysical properties directly (Section 1.4). It is likely that a combination of these two approaches will be adopted to obtain the required data. In both cases remotely sensed data are likely to make an important contribution. Given the need for global information and for spatially detailed information for many applications, data from the AVHRR sensors will be an important candidate set, because of its global coverage and relatively fine spatial resolution.

Providing data sets for the IGBP for land applications will require a hierarchical approach involving the creation of data sets at several space and time resolutions. In the present document we focus on the creation of a 1 km data set. This data set will provide a much more detailed global view of the Earth than is currently available.

2. Types and Uses of AVHRR Data Sets

2.1 Availability of Global Data Sets

Two major series of satellites, namely Landsat and SPOT, have been placed in orbit with high spatial resolution sensors specifically designed for land applications. Both of them have high spatial resolution, multispectral, sensors, which have produced many images of much of the Earth's surface. For global studies the resultant data sets are often inappropriate because of their relatively low temporal frequency, which has obstructed their use in providing regular global data sets and because their high spatial resolution has tended to result in unmanageably high volumes of data for even quite modestly sized areas.

In order to monitor vegetation at global and continental scales, the land community has increasingly turned to data from meteorological satellites and in particular to data from the U.S. National Oceanographic and Atmospheric Administration's (NOAA) Advanced Very High Resolution Radiometer (AVHRR) (Table 2.1). This sensor has a spatial resolution as measured by its Instantaneous Field of View (IFOV) at nadir of 1.1 x 1.1 km. and with its wide total field-of-view can sense the whole earth on a daily basis. Although originally designed for meteorological purposes, it has spectral bands which give useful information on vegetation. Data from AVHRR sensors have been acquired since 1981 and are expected to continue to the end of this decade.

Table 2.1. Principal Sensor Characteristics of the Advanced Very High Resolution Radiometer relevant for land cover characterization.

Spectral bandwidths	1.	580-680 nm	3b	3550-3930 nm*
	2.	725-1100 nm	4.	10300-11300 nm
	3a	1580-1450 nm*	5.	11500-12500 nm
IFOV (nadir)		1.1 km		
Swath width		2700 km		
Calibration		Absent for non-thermal bands		
Radiometric quantization		10 bit**		
Global frequency of coverage		1-2 days***		
View angle		55.4 degrees		

* Band 3a is a proposed future spectral band which will be sensed during daylight. Channel 3b which is currently sensed continuously, will only be available for night time imaging.

** Plans exist to increase the quantization to 12 bits from NOAA-K onwards.

*** This global frequency is only achievable through use of data with strongly off-nadir view angles.

2.2 Principal Applications

In terms of studies of global vegetation, the AVHRR sensor has the great advantage of collecting observations in both the red and the near infrared (NIR) parts of the spectrum. The red spectral measurements are sensitive to the chlorophyll content of vegetation and the near infrared to the mesophyll structure of leaves. Since the first is an inverse relationship and the second a direct relationship, differences between the bands and their ratios have useful relationships with several vegetative characteristics including leaf area index, percentage vegetation cover and green leaf biomass (Curran 1980). Subsequently, it has been shown that the normalized ratio of the Red and Near Infrared (NIR), namely (NIR - Red)/(NIR + Red), has a strong relationship with the photosynthetic capacity of specific vegetation types (e.g., Sellers 1985). This ratio, known as the Normalized Difference Vegetation Index (NDVI) has become the most commonly used remotely sensed measure of vegetation activity.

The potential of AVHRR data for vegetation mapping and monitoring was first reported in 1981 (Gray and McCrary 1981, Schneider *et al.* 1981, Townshend 1981). These data were initially applied at sub-continental scales. They have been used for monitoring crops within the Nile Delta (Tucker *et al.* 1984a) and they were used in Senegal for grassland monitoring (Tucker *et al.* 1983). Further studies have led to extensive application throughout the Sahel (Justice *et al.* 1985, Prince *et al.* 1990). Tropical deforestation has also been examined using these data especially in South-East Asia (Malingreau *et al.* 1985) and South America (Malingreau *et al.* 1989, Tucker *et al.* 1984b).

Using multi-temporal data sets, the seasonal variation in NDVI values has been used to discriminate between vegetative cover types (Townshend *et al.* 1991). Preliminary land cover maps have been derived at continental scales for Africa (Tucker *et al.* 1985) and for South America (Townshend *et al.* 1987) using NOAA's GVI product with pixel sizes of approximately 15-20 km. The same coarse resolution data have been to derive statistical estimates of global land cover types (Shimoda *et al.* 1986); more recently a global map of nine basic vegetation types has been produced using an integrated annual value of the NDVI (Koomanoff 1989).

At a sub-continental scale, the NASA/GSFC Global Inventory Monitoring and Modelling Systems (GIMMS) data set has been used to stratify cover types for eight countries in southern Africa as a basis for estimating the supply of fuelwood (Millington *et al.* 1989). An integrated use of GVI data with microwave data from the Scanning Multifrequency Microwave Radiometer (SMMR) has been examined (e.g. Choudhury and Tucker 1988): the SMMR data set was found to be especially useful for identifying areas of wetlands, which were difficult to distinguish with the AVHRR data alone (Giddings and Choudhury 1989). Integrated use of rainfall data sets derived from Meteosat data and the NASA/GSFC data set were shown to have potential for indicating variations in inherent land productivity (Justice *et al.* 1991).

Because of the importance of quantitative information of land cover for many aspects of global change research, under the aegis of IGBP, a pilot study is underway on land cover change and the development of procedures for creating a global land cover map at a resolution of 1 km, though the latter product is not likely to be available until later in the 1990s when comprehensive satellite data will be come available (Rasool and Ojima 1989, IGBP 1990).

Sampled and averaged data sets from the AVHRR have also been used in a variety of other ways to examine the vegetation of the Earth at continental and global scales. Firstly they provide an overview of the seasonal variation of vegetation activity (Tucker *et al.* 1985, Justice *et al.* 1985). Because the NDVI is indicative of photosynthetic activity,

attempts have successfully been made to relate its global annual variability to variations in atmospheric CO_2 (Fung *et al.* 1986, Tucker *et al.* 1986). Also based on this relationship with photosynthetic activity, a direct correlation between the annual integrated NDVI and net primary productivity of a variety of cover types has been observed (Goward *et al.* 1985, Goward and Dye 1987). The spatial variability of vegetation activity at different scales for the continent of Africa has been examined (Justice *et al.* 1991) where, contrary to expectations, most variability in the range 8 km to 256 km was found to lie at the coarsest rather than at the finest scales.

Monitoring of fires has been carried out using AVHRR in a number of areas especially with respect to fires in tropical rain forests (e.g., Malingreau *et al.* 1985, Kaufman *et al.* 1990). AVHRR data have also been directly inverted to estimate a number of biophysical properties including evapotranspiration, vegetation biomass, and net primary productivity (Goward and Hope 1989, Nemani and Running 1989). Other properties that can be estimated from AVHRR data are described in Section 1.4.

2.3 Types of AVHRR Data Sets

2.3.1 *LAC and HRPT Data*

Understanding the usage and potential of current AVHRR data sets requires comprehension of the availability and character of the various data sets derived from the basic AVHRR data with their sub-nadir spatial resolution of 1.1 km. For any one day, data at this resolution are only available for part of the Earth's surface, since they can only be acquired within line of sight of ground receiving stations (High Resolution Picture Transmission (HRPT) data) or through use of on-board tape records (Local Area Coverage (LAC) data) for a part of each cycle (see Section 3). Local 1 km archives of varying spatial extent and length of historical record are not available globally but can be obtained for parts of the globe through the NOAA LAC archive and from various national and regional reception facilities. Areas for which data sets are most readily accessible include: the North American continent, from the USGS EROS Data Center and the Canada Centre for Remote Sensing, and Europe and North-West Africa, through ESA and some European research groups. Further details of these archives are provided in Section 6 and Appendix 2.

2.3.2 *Global Area Coverage (GAC) Data*

A global AVHRR data set is acquired through on board sampling and averaging; these data are recorded and then transmitted to Earth on a daily basis and are known as GAC (Global Area Coverage) data. Each GAC pixel is created by averaging the first four pixels in a given row, missing the fifth pixel, then averaging the next four and so on until the end of the scan line. The next two scan lines are skipped completely and then the fourth line is sampled and averaged in the same way as the first. Because only 27% of each GAC pixel is averaged, relating it to specific ground areas is difficult. Other sampling schemes can readily be devised that are preferable (Justice *et al.* 1989), but this is the scheme chosen to produce GAC data, presumably because of engineering expediency. These data are usually quoted as having a 4 km resolution, but in fact their area is 16.5 sq km (based on 5 pixels with 0.1 km overlap along track and 3 pixels along track without overlap) and hence their nominal linear spatial resolution is 4.055 km. Moreover their resolution off nadir is often substantially greater.

Although global data sets of GAC data are available from NOAA, they are not in a form suited for use for global scientific applications. The data sets have to be navigated to a standard map projection and co-registered to produce multitemporal data sets. The ground size of pixels varies substantially due to the very large swath width of the

instrument and the data have to be placed on a uniform projection and resampled to assign pixel values to their new locations in order to produce geographically registered data sets.

A second major problem with the basic GAC data for land investigations is the high frequency of cloud for much of the Earth's surface. Consequently, some form of automated cloud screening procedure is required. At present the most commonly used method relies on the fact that the NDVI (or the simple difference between the infrared and red values) for clouds produces low values when compared with clear view land measurements. Hence composites in which cloud effects and other atmospheric effects are reduced (Holben 1986) can be generated by selecting the NDVI pixel value which is highest within a given time period.

2.3.3 *GVI Data Sets and Derivatives*

The most widely available global set of AVHRR Data is NOAA's Global Vegetation Index (GVI) product (Tarpley *et al.* 1984, Kidwell 1990). This set has been available continuously since 1982, though its format has changed during this time period. The GVI essentially consists of a global product with a relatively coarse resolution (>15 km pixel size) with composited images representing 7 day periods. The procedure used in its generation is as follows:

(i) Vegetation index maps are produced daily by mapping all daylight passes of the afternoon polar orbiter.

(ii) The difference between the red and near infrared values is then calculated for each day to produce the Difference Vegetation Index (DVI), which is derived from the difference between the NIR and Red channel values.

(iii) The values for each week are then selected from the date with the highest DVI to represent the seven-day period in order to reduce atmospheric effects.

(iv) The NDVI is then calculated using the values of channels 1 and 2 selected in stage (iii).

The GVI product has been generated in a number of formats. From 1982 to 1984 it was available only in a polar projection with a resolution of 13 km at the equator to 26 km at the poles. Such polar projections are especially unhelpful for global investigations of vegetation, because two separate images divided at the equator are needed to represent the Earth and there is no simple method to recombine them. Earlier studies of global vegetation therefore usually involved remapping of the GVI product by users (e.g., Justice *et al.* 1985, Hardy *et al.* 1988). A latitude-longitude (Plate-Caree) projection has been used since 1985 with 16 km resolution at the equator to 16 x 8 km at 60° N and S. In addition, all five original channels were provided along with scan angle and solar zenith angle to assist inter-annual comparisons. Further details of the NOAA GVI product are found within Kidwell 1990. As part of the IGBP, the GVI data set is being made more widely available through the Diskette Project (IGBP 1990).

Apart from the generic problems of AVHRR data outlined in the next section, the specific procedures used in creating the GVI present particular difficulties (Goward *et al.* 1992). These arise from the choice of the method of sampling and resampling the GAC data to generate coarser resolution pixels, provision of NDVI values based on the uncalibrated digital number (DN) values which introduces severe artifacts into time-series data and changes in the map projection which has been used.

In order to overcome some of these limitations of the data sets plans are currently being formulated by NOAA to produce a second generation GVI product (J.D. Tarpley, pers. comm.) and this may be generated retrospectively back to 1982. Currently a revised form of the GVI product is being prepared at the University of Maryland in which many of these limitations have been reduced.

2.4 Limitations of Existing Products

Current global products of the NDVI all have a number of limitations. The most important of these is the fact that the sensors do not have on-board calibration for channels 1 and 2, since they were originally designed purely for imaging rather than for quantitative sensing. Drift of AVHRR instruments occurs and though the changes in channels 1 and 2 partly compensate each other, substantial changes in NDVI occur due to this factor. Also the AVHRR instrument on different NOAA platforms have different gains and offsets. Consequently, inter-annual comparisons must be carried out with considerable care. The absence of calibration can be partly overcome by use of invariant ground targets to readjust the channel and NDVI values (e.g. Tucker 1989).

Problems also arise because of the limitations of the NDVI index itself. Substrate materials of soils and plant debris can have a substantial influence on the NDVI, especially where vegetation cover is sparse, and hence soil colour can have a significant effect. As a consequence, modifications of the index have been proposed (e.g. Huete 1989, Major *et al.* 1990), which help reduce, but do not eliminate, the effects of the soil background. The use of other spectral bands could possibly help to reduce soil effects to a greater extent (e.g., Crist and Kauth 1986), but currently there are no data sets with such spectral bands available at continental or global scales.

A final set of problems relate to atmospheric effects. Some of these can be substantially reduced, notably Rayleigh scattering, but the absorptive effects of water vapour and oxygen in channel 2 and especially aerosols for both channels are much more difficult to reduce. Variations in water vapour can cause the appearance of spurious greening in semi-arid areas, unrelated to any changes in ground conditions. Aerosols will also cause variations in the NDVI, and without ground instrumentation these cannot readily be corrected.

Finally the coarse resolution of the data sets in itself poses major problems because of the difficulties of accurate ground location. Moreover the high spatial variability of many land areas of the Earth exacerbates this problem, especially when detection of land cover conversion by anthropogenic action is of importance, since the resultant changes have particularly high spatial frequencies (Townshend and Justice 1990).

2.5 Data Sets Under Preparation

An improved product at higher spatial resolution is currently under production by the GIMMS group at NASA's Goddard Space Flight Center. GAC data are reprojected onto an equal area projection and resampled by continent to create a data set with a spatial resolution typically of about 7.6 km corresponding to the size of basic GAC pixel at view angles of 35^0 off nadir. Thus near nadir pixels are somewhat over-sampled and pixels from higher view angles are under-sampled.

The digital number (DN) values are converted using available calibration data, which is limited in amount and quality. A simple procedure for cloud detection is applied by thresholding channel 5 temperatures. The NDVI is then calculated for each date, with zeros being included where clouds have been flagged.

Composites are subsequently generated by selecting the highest NDVI value for a 15 day period of each pixel for all continents except Africa where the period is 10 days because of operational requirements of the Food and Agricultural Organization (FAO). Data are currently being composited by continent. The resultant product is therefore substantially different from the NOAA GVI product in terms of its spatial resolution, projection, cloud clearing procedures and the values used to actually calculate the NDVI.

Experience with the GIMMS product is providing the basis of a NASA/NOAA-sponsored AVHRR Land Pathfinder data set, which is being created to act as precursor for the international Earth Observing System (EOS). Current plans are to generate a global data set at 9 km resolution retrospectively to 1982. A related product is also being created at the European Community's Joint Research Center (JRC) at ISPRA. As a first step, the JRC Monitoring Tropical Vegetation (MTV) project has produced a daily GAC product with all five channels for west Africa covering the period from July 1981 to August 1989. Daily NDVI and 10 day maximum NDVI products are also available. The MTV project is currently extending this process to the whole of Africa for which a multi-channel, daily time series at 5 km resolution is being produced. This data base includes all channels as calibrated data, NDVI, surface temperature and a cloud mask (Belward *et al.* 1991).

Table 2.2 summarizes the current availability of AVHRR data sets. It should be apparent that there are no plans being implemented to provide global coverage at better than 9 km resolution in the form of the AVHRR Land Pathfinder data set. Basic GAC data are archived by NOAA, but it should be recognized that they are not available in a form which allows usage by those interested in land applications at global scales.

Data at 1.1 km resolution are currently available at best only on a regional basis. Compilation of a global data set at 1.1 km resolution to address the scientific requirements outlined in Section 1 will therefore require a new international effort, underwritten by substantive support of national agencies.

2.6 Future Sensing Systems

Data with a spatial resolution comparable with that of the AVHRR are expected to become available from various new sensors during the present decade. In the immediate future the most important of these is likely to be the Along Track Scanning Radiometer of the European Remote Sensing satellite (ERS). This instrument has the capability of viewing the same target from two different look angles to assist atmospheric correction. The instrument on board ERS-1 senses only in the thermal and its objectives are mainly to improve estimation of sea surface temperature. However the instrument to be included on ERS-2, due for launch in 1994, will have a visible and a near infrared bands. The system has the tape-recording ability to record data for the whole of the Earth's surface though its temporal resolution will be lower than that of the AVHRR.

Substantial improvement in medium resolution sensing will be achieved with instruments of the Earth Observing System notably the US Moderate Resolution Imaging Spectrometer (MODIS) (Ardanuy *et al.* 1991). MODIS will have substantial benefits for land cover classification and other tasks of land cover monitoring compared with the AVHRR (Townshend *et al.* 1991).

Table 2.2. AVHRR land cover data sets: current and future availability*

Name of Data Set	Agency	Spatial Resolution**	Coverage	Availability
Global Vegetation Index (GVI)	NOAA	15-20 km	Global	1982-present
Diskette Project	NCAAR	15-20 km	Africa Global	1982-89 ***
Modified GVI	UMCP	15-20 km	Global	1988 (Future 1982-90)
GIMMS Product	NASA/GSFC	7 - 8 km	Africa N. America S.America Asia Australia Europe	1982-1990 *** *** *** *** ***
Land Pathfinder	NASA/NOAA (by 1994)	9 km	Global	1982-present
TREES	CEC/ISPRA	1.1 km & 4 km	Tropics	***
1 km Product	USGS/EROS	1.1 km	USA	***
1 km Sharp Product	CEC/ISPRA	1.1 km	Europe	***

* Archives of AVHRR data requiring substantial processing before usage are not included.
** In this context spatial resolution refers to the bin or pixel size of the product.
*** Information not available.

GIMMS: Global Inventory Monitoring and Modelling Systems
TREES: Tropical Ecosystem Environment Observations by Satellites

MODIS consists of two instruments, one with a nadir view for land and atmospheric applications (MODIS-N) and one with the ability to tilt and provide off-nadir views (MODIS-T), primarily for oceanic and secondarily for land applications (Magner and Huegel 1990). A moderate resolution instrument, mainly for oceanic applications is being developed by the European Space Agency, known as the Medium Resolution Imaging Spectrometer (MERIS). An advanced version of the AVHRR known as AVHRR-4 is currently being planned by NOAA, but is not expected to be in orbit until the end of this decade.

Undoubtedly these and other instruments will provide data with much greater capabilities than the current AVHRR instrumentation, but this sensing system will be the prime provider of moderate resolution data of the land surface for several more years.

2.7 Conclusions

A review of the literature has demonstrated the value of AVHRR data in a wide range of activities relevant to the objectives of IGBP. The application of these data has been hindered both by the limitations of the sensor, but also by the limitations of available data sets compiled from this sensor.

Currently the only complete multi-year global AVHRR data set is the NOAA GVI product, which has a spatial resolution of 16-20 km. Moreover it has significant problems associated with calibration and processing. Continental data sets are being generated with a resolution of approximately 8 km at the NASA Goddard Space Flight Center. Under a joint NASA/NOAA Pathfinder activity, multi-year data sets with a uniform spatial resolution of 9 km will be created in the next few years. However there are no plans at present to produce global data sets at any finer resolution. It is proposed therefore to develop a global data set directly from AVHRR 1.1 km data. The following sections of the document explain how this could be achieved.

Creation of a "1 km" data set will also allow coarser resolution data sets to be produced, undistorted by the consequences of the peculiar sampling and averaging procedure used to create the Global Area Coverage (GAC) data set (Justice *et al.* 1989 and Section 2.3) on which all current AVHRR global data sets are based. Other applications will require even more detailed data sets derived from Landsat and SPOT, though they will only be available more locally and less frequently than those data sets derived from AVHRR.

A number of actions will be needed to provide adequate global data sets:

(i) An effort to develop a 1 km data set should begin immediately, to ensure product availability in a reasonable time-frame (2 - 5 years). This will also have the benefit of creating a set of test bed data, which will overlap with the MODIS instrument of EOS.

(ii) It is important to increase utilization available remote sensing data at 16 km resolution along with registered cartographic data sets.

(iii) At the same time concerted efforts need to be maintained in the definition and building of data sets with a resolution at about 8-10 km from the existing archive of NOAA AVHRR data, and there should be immediate efforts to create a global land cover product data set.

(iv) Finally, the need for data sets with finer spatial resolution reliant on data from SPOT and Landsat, alluded to in Section 1, also needs to be recognized.

3. Required Characteristics of the 1 km Data Set

3.1 Introduction

In an ideal world, data acquisition and compilation should be tailored to satisfy specific needs as defined by a particular application. In the real world compromises have to be made so that available data sets satisfy a range of sometimes very diverse requirements. The components of this compromise pertain not only to the data requirements, but also to the availability and characteristics of sensors and to the current capabilities to handle the volumes of data arising from repetitive coverage of the land surface. The search for a common denominator for all these needs and constraints is, therefore, crucial to the success of defining and producing useful global data sets.

The present section considers some of these requirements which can be put forward in order to satisfy as closely as possible the scientific needs expressed in Section 1. It is a challenge to define an all-encompassing satellite product which will satisfy all these various needs. A common requirement of all possible applications is data sets of calibrated and accurate measurements of surface radiometric characteristics. Such data sets can then be used to derive physical quantities and biophysical characteristics of ecosystems using inversion algorithms. This double inversion - from satellite radiometric measurement to physical quantities and from physical to biophysical quantities - represents the essence of quantitative remote sensing analysis. Because it is more mechanistic, the first step is usually part of the preprocessing stage of data preparation, details of which are described in Section 5. Most of the applications of the second inversion are still at a development stage (see Section 1.4). Here discussion is limited to a set of general considerations pertaining to the desired characteristics and availability of a global satellite data set of land surfaces. This section is completed by a list of key issues related to the compilation, management and utilization of those data sets.

3.2 Spatial Resolution

The question of appropriate spatial resolution is very much at the core of global monitoring. The resolution provided by the sensor IFOV (Instantaneous Field of View) must be such that it not only satisfies information requirements through spatial discrimination of 'objects' or variations in a parameter field but also that it does not unduly overload the data flow associated with a global coverage. Studies have indicated that resolutions finer than 1 km are highly desirable for change detection in a range of landscape types (Townshend and Justice 1988). The same authors found that a compromise of 500 m is acceptable. It must be emphasized however that the relationship between information content and spatial resolution is usually non-linear and that there are resolution 'windows' associated with a given landscape. It can also be shown that the spatial heterogeneity of a landscape is seasonally dependent and that a variable spatial sampling rate can at the same time provide adequate resolving power and reduce data loads (Malingreau and Belward 1991). Designing a system flexible enough to accommodate these variable minimum resolution requirements could help in alleviating the burden of data volume implied in a continuous global 1 km processing.

The so-called 'one-kilometre' data offered by the AVHRR sensor can be considered as an acceptable compromise between ground resolution and data loads for continuous monitoring (TREES 1991, Malingreau and Belward 1991). But, to date, global coverage has yet to be attempted and current experience is confined to regional monitoring exercises in areas such as North America, Amazon, West Africa and South-east Asia (TREES 1991) and for selected periods of time, such as the dry season for deforestation studies and the growing season for grassland or agriculture. The regional projects which are currently under development for IGBP's pilot study areas for land cover investigations (Rasool and Ojima 1989), The International Space year (ISY) project on tropical forest belt for forest monitoring, the Agricultural Monitoring programme of the Commission of the European Community (CEC) and other objectives, could represent build ing stones in developing a global monitoring system. However, it must be remembered that several of these projects have needs and *modus operandi* which are not necessarily compatible with IGBP objectives.

While a consensus exists on the desirability of a 1 km coverage (Sections 1.5), current experience (or the lack of it) warrants a thorough comparison of scales and in particular a systematic comparison between the original 1 km and the resampled 4 km data set (GAC). This is justified by (i) the existence of global GAC data sets since early 1982; (ii) the central availability of such GAC archive; (iii) the 16-fold reduction in data volume afforded by this product.

It would, in particular, be of interest to assess the advantages of linking the inter-annual and seasonal information obtained from the GAC time series with the spatial and spectral information content of the 1 km product. If a 1 km data set is created and if it has sufficient reliability and a truly global coverage, it could form a better basis for coarser resolution data sets than current GAC data, given the peculiar sampling and averaging procedures used in their generation (Sections 2.3.2 and 2.7)

3.3 Repetivity

Daily coverage by the AVHRR is a major advantage, because of its very wide swath angle. The importance of this characteristic is related less to the need for daily data on the status of the vegetation canopy, which would be a stringent and unusual requirement, than to the beneficial impacts of daily revisiting on the probability of obtaining scenes of acceptable quality. However, it is important to remember that most of the AVHRR swath does not possess the nominal 1 km ground resolution due to across-scan geometric distortion and to registration problems in assembling time series. Furthermore, data obtained at extreme angles are affected by an excessive atmospheric impact due to the long path lengths.

Without going into full treatment of the AVHRR geometry, it is important to note the following. Orbit and swath geometry of the AVHRR instrument is such that the same orbital trace is covered every 9 days at the equatorial crossing. That is, an area at nadir of the satellite, where the IFOV is at a nominal 1 km resolution can be covered with a nine day frequency. If a larger portion of the swath is used, the revisiting frequency increases until a daily coverage is assured. An increasing view angle means, however, an increase in the 'pixel' size, which, at the edge of the swath, can reach 6.7 x 2.45 km. Also, taking account of atmospheric interference, a common rule of thumb is that the most usable area of an AVHRR swath width is contained within ±15° of nadir from the total swath width of 25° where the IFOV is maintained within 1.5 x 1.5 km. The revisiting period for that part of the orbital cover is approximately 6 days.

Why then collect daily data? Increasing the revisiting frequency is one way to increase the probability of having a clear day coverage of a selected area.

Furthermore, when the central part of the orbital swath is affected by bad weather conditions, data for that portion of the land surface may have to be derived from other orbits at larger view angles in order to avoid holes in the coverage. Consequently practically all the orbits have to be collected and decisions are only made on which data will be retained in the final product, at the time of 'mosaicking' or 'compositing.'

The above discussion points to critical needs in two distinct steps of the preprocessing: (i) geometric and atmospheric correction which can cope with views that are off nadir, and (ii) compositing of daily data into synthetic products in order to maximize the frequency of cloud-free coverage (see Section 4).

3.4 Geographical Coverage

The prime concern in terms of geographical coverage is that data of the whole land surface are acquired. Because of the limitations of on-board tape recording and receiving capabilities of ground stations, a reliable global geographical coverage at 1 km resolution can only be achieved by significant use of a distributed network of receiving facilities which can operate in the HRPT mode. Section 5 describes the current situation in terms of the location of receiving stations and their recording policies. Two contrasting policies could be pursued to acquire the global data set. The first one would rely entirely upon the selection of a series of corresponding stations which would ensure the wall-to-wall coverage. The second approach would be to rely upon the on-board recording facilities to collect a core data set supplemented, when required, by station acquisitions. These two options are now discussed.

The collection of data from a distributed network of receiving stations presents logistic difficulties which should not be underestimated. Each station usually has its own reception schedule, and stores and archives the data according to local resources and policies. A joint international effort has recently made by the EROS data center, ESA, NASA and the JRC to assess the current holdings and reception policy in a wide range of stations distributed around the world. This represents an important step in putting together the basic documentation needed in order to plan a collection strategy. The specifics of how to secure the appropriate data set from these stations are still to be spelled out, and the continuing role of the IGBP in that process has not yet been defined. The current ISY Forest Watch and CEC/JRC-ESA TREES projects have included attempts to establish such specifications for carrying out this very exercise with respect to the needs of global tropical forest monitoring.

A reliance on the LAC acquisitions received at NOAA presents the advantage of centralizing a significant part of the global archive. It must be recognized, however, that a truly global coverage can only be obtained by drawing upon supplementary stations around the world (see Section 5). A drawback to this mixed approach is that it will limit the potential involvement of individual stations or countries in any sort of cooperative international venture. Experience has shown that given the right incentives, whether they are scientific, financial or institutional, many satellite receiving stations can perform a very adequate task. Difficulties linked to the multisource approach should, however, be clearly assessed if global coverage has to be acquired within a short time-frame.

The previous discussion suggests the adoption of a pragmatic approach to the formation of a global data set in the framework of the IGBP. Obviously, priority areas must be defined. These include areas where IGBP Core Project activities are taking place, Pilot Study Areas as defined by IGBP-DIS and possibly other regions deemed critical in a global change perspective. In addition, the global exercise should also rely upon the regional studies currently underway. A strategy to do so has yet to be devised and a complete catalogue of such priorities and its companion strategy will need to be established.

3.5 Length of Record

The question of the time length of the 1 km data record arises with particular reference to the intended application. Again, needs can diverge. It has been shown for example that preliminary estimates of deforestation in the tropical evergreen forest can be obtained using a limited but appropriate set of AVHRR data (Malingreau and Tucker 1988, Malingreau *et al.* 1989). The variable frequency necessary to monitor agricultural scenes as the crop evolves is another case in point. The appropriateness of the record also depends upon the quality of the data, including attributes such as view angle and atmospheric conditions, and scene characteristics, notably phenological stage. A world archive which will best cope with a wide variety of requests can either be a collection of time and space windows (acquired upon specific requests) or be all-encompassing and draw upon complete world daily coverage. In the first case the acquisition window is selected to fit the problem at hand in the particular latitudinal zone. In the second case, the entire data set is made available to the researcher who can then extract required windows of interest. Ideally data in both formats should be available.

A complete year of images is the minimum which must be acquired for a world data set considering the seasonality of vegetation. However, it must be emphasized that inter-annual differences in vegetation growing patterns contain important signals related to human and climate impacts. Data for a single year would therefore offer a relatively static type of information, even if it describes a complete annual cycle of seasonal variation. Significant progress will need to be made in the existing international collaborative arrangements, to ensure the compilation of a reliable multi-annual global 1 km data. If multi-year data cannot be generated then the coupling of the 1 km AVHRR data set with the GAC product, which yields global coverage year after year, may offer a useful alternative approach.

Finally, the global data set must be drawn from at least one complete specific year and not be extracted from an heterogeneous assemblage of 'good' data as they happen to be found in the archives. This is not discounting the value of demonstration products (e.g., continental mosaics) based upon the best data available in the archive. Unlike the NOAA/NASA AVHRR Pathfinder activity, the prospects for creating a retrospective data set are poor, because of the lack of global systematic collection of data at this resolution.

3.6 Bands to be Included Within the Global Data Set.

Although the most commonly used products from the AVHRR have been various vegetation indices, especially the NDVI, it is important that the original channels are also included. This is needed because of the possibility of deriving other spectral indices; the independent discriminatory value of the individual bands; and the use of the latter in deriving biophysical properties by inversion and statistical procedures.

The main objectives in generating this data set will be to contribute to the work of IGBP scientists. As such it is important that the products are easily applied by users. One major way that this can be achieved is by relieving users of the task of various preprocessing procedures, the most important of which are the following:

(i) Radiometric calibration to reduce variability of sensor response through time, both within and between sensor data sets, especially for bands 1 and 2 where the absence of on-board calibration makes vicarious procedures essential (see Section 4.3).

(ii) Atmospheric correction of bands 1 and 2, so far as is feasible, using agreed algorithms (see Section 4.4).

(iii) Geometric correction to ensure a high degree of spatial registration, preferably of less than 1 pixel. Without such high standards of registration many of the differences between images will be spurious, and users will be forced to carry out a further stage of geometric correction (see Section 4.5).

(iv) Images must be composited to reduce the impact of clouds, and the problems of data handling.

The distributed products should therefore have had these pre-processing procedures already applied. Discussion of the precise details of the content of the data set is given in Section 4.2 In summary, it is recommended that calibrated data are provided for all channels and that for channels 1 and 2 atmospherically corrected data are also included. Consideration will also need to be given to making the uncorrected data available to allow more sophisticated users the opportunities to apply their own improved corrections.

3.7 Other Characteristics of Global Data Products

Technical issues related to the production of a fully global and repetitive 1 km satellite coverage of the land surface are covered in detail in Sections 4-6. A short note is due, however, on the need for users to have access to data in a standardized format including all necessary information on calibration, navigation and angular information on the sun and satellite locations. This will allow a more informed use of the data sets and assist research work on algorithm development for the derivation of physical parameters.

In addition, there is a growing portion of the user community which requires data sets already processed into geophysical variables of interest such as albedo, surface temperature and vegetation indices. The development of such advanced data sets must be seen as an important means to stimulate the interest of a new community of scientists directly involved in the biogeochemical issues which are at the core of the IGBP programme.

3.8 Associated Issues

A number of related issues need to be considered if a satisfactory global remote sensing data sets are to be created:

(i) There is currently a lack of explicit consideration of how to cope with the physical dimensions of high resolution global data sets, such as the 1 km data set considered here, especially with respect to the logistics of archiving, distribution and associated processing logistics. While current computing facilities can easily cope with data volumes, serious bottlenecks are likely to exist at the input/output levels.

(ii) Integration of satellite-derived physical parameters into models of ecosystem functioning represents the biggest challenge of the undertaking: this is where research effort should be concentrated. The task is hindered by the current shortage of people to bridge the gap between the physical and biological sciences. The IGBP effort should focus on filling part of this gap by stimulating the interest of ecologists and plant scientists on the new possibilities offered by the observation of the Earth surface using remote sensing instruments from space.

(iii) The acquisition of contemporaneous high resolution data (SPOT, LANDSAT) must be considered using a sampling scheme designed at the biome level. High resolution data sets are in all cases necessary for local scale studies and in many instances are used as proxy field verification. There is at present no strategy for sampling at such scales. Recently there have been major reductions in the price of Landsat MSS data older than two years; these reductions should greatly increase the availability of historical Landsat data and should facilitate the application of multilevel approaches.

4. Pre-processing Procedures

4.1 Background

AVHRR data are transmitted to ground stations in many different countries worldwide. In principle it is possible to produce global, consistent AVHRR data sets by merging products generated in various locations around the world, since it is the same sensor which generates the data. However, to achieve this objective, a consistent approach to the pre-processing of the data must be employed, including the use of identical algorithms and, as far as possible, identical coding in computer software. The former, in particular, is a prerequisite for combining data from various stations into a radiometrically and geometrically seamless global product. Such a product should have no artifacts induced by differences in data handling on the ground.

Precedents for the definition and implementation of such procedures have been set by the processing of data from high resolution sensors such as the Landsat Multispectral Scanner System (MSS), the Landsat Thematic Mapper (TM), and the SPOT Haute Resolution Visible (HRV) scanner. Generation of data sets from these programmes entailed significant and costly efforts both to define optimal procedures for production of standard data sets with the necessary radiometric and geometric corrections, and also to implement these procedures in a coordinated fashion at ground stations around the world. Such activities were supported by significant and focused research programmes aimed at optimizing the pre-processing steps and making the most effective use of the satellite data.

Unfortunately, similar levels of effort or support have not been provided for data sets from the AVHRR sensor. The principal reason was the initial perception of the purpose of the instrument as a 'weather sensor.' When some research groups realized the unique value of these data for Earth resources studies, funding was limited as well as fragmented. In addition, because of the emphasis on applications, insufficient resources were available to define adequate pre-processing methods. Thus AVHRR data were processed locally by various groups around the world for diverse uses and often on systems originally developed for other purposes. Nevertheless, research results during the 1980s demonstrated the value of the AVHRR data for continental and global monitoring, and these have been complemented by progress in understanding how these data should be handled.

Recent discussions in the scientific community (e.g., Teillet 1989, Gutman 1990) resulted in substantial agreement on the best procedures that can presently be specified for the pre-processing of AVHRR data. This section thus describes procedures recommended by the scientific community for the processing of AVHRR data intended for land applications. In addition, numerous issues need to be dealt with to further improve the quality of the final product; these are discussed in Section 4.8.

4.2 Data Processing Flow, Compositing and Output Products

In general, individual AVHRR images should be corrected radiometrically and geometrically, and subsequently those pixels, which are least contaminated by atmospheric interference, should be selected. Image size can vary depending on whether data are stored from part of an orbit to a complete orbit or even several orbits.

In the context of the applications discussed in Section 1, each image should contain all 5 channels at 10 bits.

The recommended AVHRR data pre-processing sequence is as follows:

(i) modelling the satellite orbit
(ii) location of ground control
(iii) establish transformation to map projection
(iv) radiometric calibration (Section 4.3)
(v) atmospheric correction (Section 4.4)
(vi) computation of NDVI and geophysical parameters
(vii) geometric correction and resampling (Section 4.5)
(viii) compositing (Section 4.6)
(ix) generation of output products.

General standards have not yet been established for items (i) and (ii). Various approaches have been developed, consisting of orbit models with different accuracies and employing ground control points to various degrees. However, the principal requirement here is to ensure sub-pixel accuracy of the final product, at the resolution adopted. Depending on the level of sophistication of the orbit model and the transformation algorithm, few or many ground control points may be required. The question of which map projection has to be used is a key issue for the definition of a global data set and is discussed separately in Section 4.5.

In order to reduce the effects of cloud contamination and to reduce various other atmospheric effects, a compositing procedure is often adopted when using AVHRR data (Holben 1986). Compositing involves the merging of two or more images of an area: ideally for each pixel the date of acquisition of each pixel is retained. Since it is presently not possible to specifically identify all cloud-contaminated pixels, an indirect method selecting the least contaminated pixel among all available images, needs to be employed. The currently accepted procedure is to output the input pixel with the highest NDVI value from all input images. Further discussion on compositing is provided in Section 4.6.

In implementing the data processing flow, block-based processing and radiometric look-up tables are recommended; however, the details may differ from one system to another. One effective implementation scheme is discussed in Appendix 1.

It is recommended that the basic output data set resulting from preprocessing contain the following 10 bands:

(i) maximum NDVI
(ii) channel 1, calibrated and corrected for radiometric and atmospheric effects
(iii) channel 2, calibrated and corrected for radiometric and atmospheric effects
(iv) channel 3, calibrated
(v) channel 4, calibrated
(vi) channel 5, calibrated
(vii) solar zenith angle
(viii) satellite zenith angle
(ix) relative azimuth between sun and satellite
(x) date and identification of the source image for the selected NDVI.

It is very important to maintain full radiometric resolution in the processing stream as well as in the output product. This resolution is 10 bits for existing AVHRR sensors, and will increase to 12 bits in the future. Ancillary information on such matters as the calibration coefficients utilized should also be included.

The overall scheme for AVHRR correction is shown in Fig. 4.1. Consideration will also have to be given to the possibility of providing uncorrected data so that more sophisticated users can apply their own calibration and correction procedures.

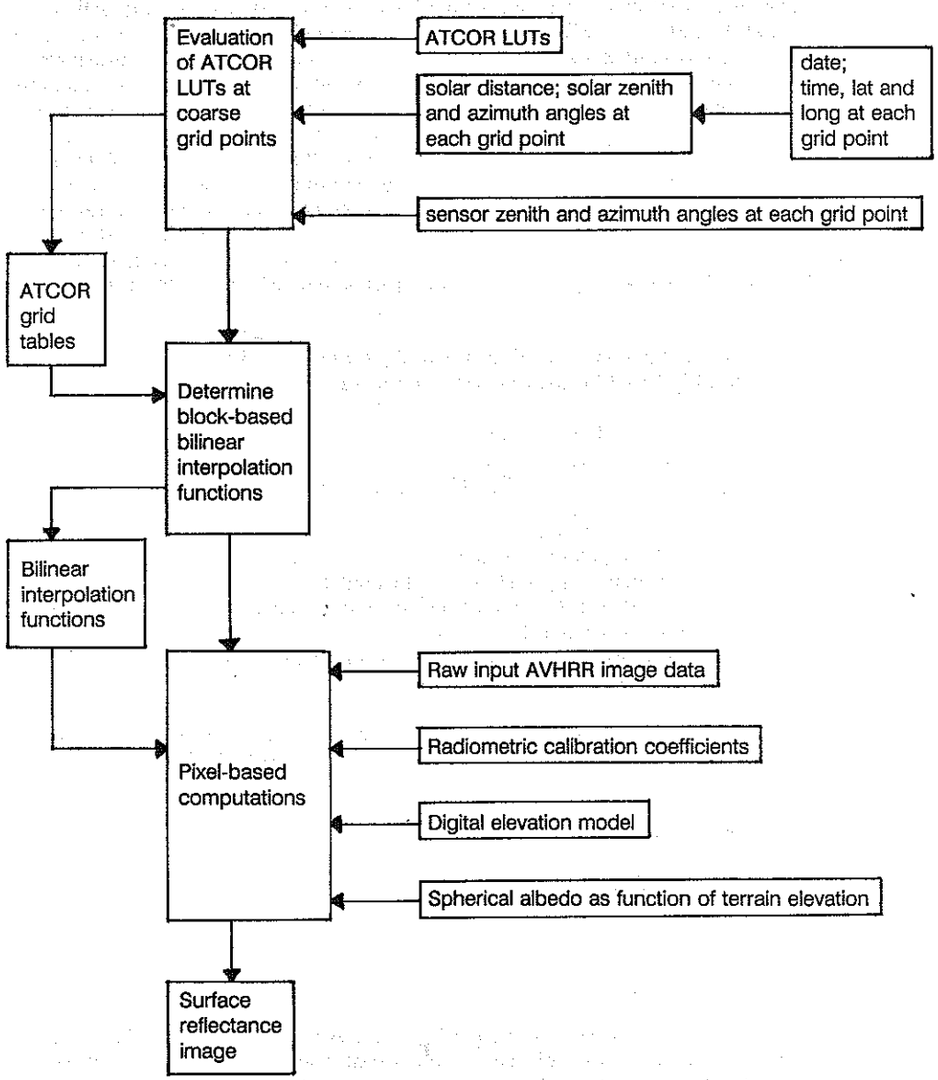


Fig. 4.1 AVHRR radiometric and atmospheric correction data flow

4.3 Radiometric Calibration

Preprocessing of AVHRR data should include calibration of all five channels. A major issue here is the uncertainty associated with proper calibration of channels 1 and 2. Calibration data are only available from ground-based measurement and there is no subsequent on-board calibration. This is an important issue since calibration coefficients change following the placing of the sensor in orbit, sensor performance subsequently degrades, and the different AVHRR instruments vary in performance. A variety of approaches are being used to monitor the observed degradation in sensor performances and, although they show comparable trends, the results from the different approaches are often not in close agreement (Teillet 1990a). Several research groups monitor changes of sensor performance and there is an increasing consensus from this community on agreed coefficients (e.g., Holben *et al.* 1990, Kaufman and Holben 1990, Teillet *et al.* 1990, Brest and Rossow 1991). These coefficients are often only determined retrospectively, thus highlighting the importance of data archiving to meet the need for data reprocessing. In this respect, it would be of considerable interest and use to have a periodic bulletin updating calibration coefficients for the AVHRR and other key remote sensing systems. The bulletin should be relatively brief, very widely disseminated, and issued once or twice a year.

For channels 1 and 2, the apparent reflectance at the sensor should be computed using the following relationship based on equation (1) of Appendix 1:

$$\rho^* = \frac{D - D_o}{G} - \frac{\pi d_s^2}{E_o \cos\theta_s}$$

where:

- ρ^* = apparent reflectance
- D = digital signal level (counts)
- D_o = zero-radiance digital signal level (counts)
- G = gain coefficient (counts/(W m^{-2} sr^{-1} μm^{-1})), where sr refers to steradians
- d_s = solar distance (A.U.)
- E_o = exo-atmospheric solar irradiance for the channel (W m^{-2} μm^{-1}),
- q_s = solar zenith angle (degrees).

It should be noted that prelaunch calibration coefficients given by NOAA (Lauritson *et al.* 1979, Kidwell 1986) are expressed in terms of effective normalized albedo A (in per cent) such that:

$$A = \gamma D + \delta = 100\, \rho^* \cos\theta_s d_s^{-2}$$

Therefore, the correspondence between coefficients is given by:

$$G = \frac{100\,\pi}{E_o} \quad \text{and} \quad D_o = \frac{-\delta}{\gamma}$$

Scene or pass averages of the space-view portion of the AVHRR mirror scan should be used for the zero-radiance offset values. Given the relatively stable behaviour of these offsets for AVHRR, values obtained from a scene or pass within a few hours or days of it being processed will be adequate. Nevertheless, data processing software should be able to read and use the space-view data.

For exo-atmospheric solar irradiances, values from Neckel and Labs (1984) or Iqbal (1983) are recommended.

When formulating detailed calibration procedures, the operational use of calibration coefficients involves two considerations. One is the calibration of retrospective AVHRR data based on the best available results over time for each instrument. The second is the extrapolation of recent calibration results for processing data on a near real-time basis. Hence, there is a need to establish well characterized historical trends and a need to update calibration data with sufficient frequency. If changes in the gain of the AVHRR through time can be characterized, interpolation should be used to estimate calibration coefficients between updates.

4.4 Atmospheric Correction

The impact of atmospheric effects on the value of the NDVI is of the order of 0.02 - 0.04 (in NDVI units) for Rayleigh scattering, 0.04 - 0.08 for water vapour absorption, and 0.04 - 0.2 for aerosol scattering. A Rayleigh scattering correction, including adjustment for base topography, should be part of the AVHRR preprocessing in channels 1 and 2. Recommended reference values for Rayleigh optical depths for standard pressure and temperature conditions for standard atmospheric models are available (Teillet 1990a, Teillet 1989). The best available global digital terrain model should be used to account for local elevation. As of 1990 this is ETOPO5 (NOAA/National Geophysical Data Center 1989), but in the future it will probably be the Digital Chart of the World (DCW).

Although there is presently no agreement as to which atmospheric radiative transfer code should be used, it should be noted that most of the better codes tend to disagree substantially only for large optical depths for aerosols and large off-nadir angles of 60° or more. The proper use of a given atmospheric code should therefore be of greater concern than which code to use. For example, monochromatic radiative transfer computations should not be used to represent AVHRR channels 1 and 2 (Teillet 1989). Bandpass calculations based on 0.005-micrometer spacing or better are recommended.

A correction for ozone in channel 1 should be based on concentration values from standard climatic tables with latitudinal and seasonal dependence (Teillet 1990a).

Several possible approaches for the correction of water vapour absorption exist, but there is no community agreement on an acceptable method. The following possibilities exist:

(i) A standard climatology with latitudinal, longitudinal and seasonal dependence would allow a rough correction to be implemented easily, although it would clearly not capture day-to-day or spatially localized variations. The McClatchey atmospheres would be the standard data sets in this case (McClatchley *et al.* 1971).

(ii) Water vapour concentration from a world-wide grid of radiosondes or from meteorological satellites are now available. Although the acquisition and use of such data may not be straightforward and there are likely to be discontinuities in coverage, the NASA WetNet project has provided improved estimates of columnar precipitable water.

(iii) Channel 4 minus channel 5 temperature values tend to be correlated with water vapour and may provide a reasonable method; however, it requires further validation.

(iv) Data from the Advanced Microwave Sounding Unit (AMSU), starting in 1993, may provide the necessary information on water vapour for future AVHRR images.

Another difficult problem is the correction for aerosol scattering corrections. The following options exist at present:

(i) Apply no correction, i.e. assume aerosol optical depth is negligible or zero.

(ii) If a standard climatology with latitudinal, longitudinal and seasonal dependence can be identified, it would allow a rough correction, although clearly it would not capture day-to-day and spatially localized variations and it might not lead to any substantive improvements.

(iii) Sun-photometer grids have been proposed for some parts of the world, such as parts of Africa, where the aerosols vary considerably both spatially and temporally.

(iv) There are satellite sensors (such as SAM-II) that measure aerosols, but the use of such data in operational processing is far from straightforward.

(v) There is a NOAA product that provides aerosol optical depths over the oceans and other large bodies of water, but it is not obvious how to achieve a comparable product over land. AVHRR pixels are large and generally preclude the use of dark targets or targets of known reflectance to estimate path radiance and hence aerosol optical depth. Where sufficiently large water bodies and areas of dense green vegetation can be identified, the dark-target approach may be used in the future (Kaufman 1989).

Based on an extensive observational data set, research at the Canada Centre for Remote Sensing (CCRS) (Ahern et al. 1991) identified a commonly occurring aerosol condition for very clear atmospheres near Ottawa, Canada, namely an aerosol optical depth of 0.05 at 550 nm, and a Junge exponent of 3.5. Because the NDVI compositing process tends to select clearer atmospheric conditions, there are plans at the CCRS to use this aerosol optical depth as a minimum correction. However, since aerosols in other parts of the world do not necessarily have the same character, it may be preferable not to apply a uniform aerosol correction until a more general approach is developed.

Appendix 1 describes an algorithm to retrieve surface reflectance from AVHRR channels 1 and 2.

4.5 Geometric Correction

Geometric correction involves precise transformation of the image from the sensor-based projection to the earth surface-based projection. This includes orbit calculation and/or selection of corresponding pairs of control points from the image and ground, and resampling of the source image to determine channel values for each output image. The first two items primarily control the resulting positional accuracy (see also Section 4.2). Resampling is important because the particular method chosen necessarily affects the radiometry of the output image. Various resampling algorithms have previously been used and a considerable literature is available on this subject (e.g., Shlien 1979, Bernstein 1983). In principle, resampling should have a minimal effect on image radiometry, and the algorithm should be chosen with this criterion in mind. In addition, arithmetic operations involving band combinations such as the NDVI should be carried out before resampling wherever possible, again in order to minimize the effect of the latter. For consistency, one resampling algorithm should be chosen for the global AVHRR data set. One possible candidate is the 16 point damped sin(x)/x resampling kernel. However, further research on this subject is needed (see Section 4.7).

To date, each of the main processing groups have used the projection considered most appropriate for the particular geographic region of interest and the objective at hand. A readily available and globally applicable projection is the geocentric projection in which each pixel has a standard size in degrees of latitude and longitude respectively. This projection has recently been employed for global and regional data sets in both raster and vector formats (Cihlar *et al.* 1990). Although globally applicable, this projection has a drawback in that the pixels do not represent areas of equal size at the surface; this becomes more serious at higher latitudes. Although computationally this can be easily overcome, the oversampling at higher latitudes leads to inefficient data storage, and it distorts the display of such data sets unless reprojected on display. A spherical coordinate system for equal area mapping has also been recommended as appropriate for global NDVI data sets (Goward 1990). The Committee on Earth Observation Satellites (CEOS) has considered this issue, and standards or consensus may be expected to emerge. Ultimately, the most important consideration is the ability to transform the data to other projections; flexibility is therefore essential.

4.6 Compositing Period

In principle, the length of the compositing time period depends on the type of application, geographic location, cloud cover frequency, and other factors, though for a global data set there are clear benefits for a single period to be adopted for the sake of uniformity. A period varying between 7 and 14 days has been used most frequently to date. Where a single compositing criterion is used, such as the NDVI, longer compositing intervals based on integer multiples of the basic period are readily possible. It is recommended that for global uses 10 days should be the standard minimum compositing period. For composites based on a single criterion, this will allow the compilation of continental or global data sets over time periods ranging from 10 to 30 days or more. For more regional studies at higher latitudes, a five day compositing period is feasible because of the much greater frequency of imaging in these localities. However, the selection of standard compositing periods is far from straightforward and further research may be warranted (Section 4.7).

4.7 Research Issues

Although the basic procedures for preprocessing AVHRR data can be defined with confidence, this does not mean that all the issues have been resolved. Rather, the understanding of problems is sufficient to enable the specification of a methodology that will permit the development of globally consistent data set with acceptable accuracy for many applications. It is important that research continue in parallel to address outstanding questions in order progressively to improve products. This of course presupposes that raw AVHRR data will be archived to permit re-processing in the future. The following issues deserve particular attention.

(i) *Compositing.* Currently a single criterion is often used for selection of the highest NDVI in a given time period. Alternatives should also be investigated. Possibilities include using the average of highest NDVI values, or use of thermal channels. Also a study should be undertaken on whether atmospheric correction of selected maximum NDVI values is better than selecting the maximum of the atmospherically corrected NDVI. Further work is needed on the optimum length of compositing period, possibly as a function of geographic location. A better understanding as to why, in some studies, maximum NDVI has been found to favour the forward scattering direction at off-nadir pixels is needed. In this respect, care must be taken to allow for biases as a result of the location of receiving stations.

(ii) *Cloud screening.* Various procedures should be investigated, including consideration of the stage within data analysis when such screening should be carried out. More reliable cloud-screening procedures would allow retention of all data not contaminated by clouds, thus improving the spectral characterization of the surface.

(iii) *Bidirectional reflectance distribution function (BDRF).* Calibrated and atmospherically corrected AVHRR data will provide NDVI values that are still subject to variations due to surface reflectance characteristics. Research on BDRF is therefore a high-priority area, and should provide a fundamental contribution to the compositing process.

(iv) *Aerosol correction.* Approaches to aerosol corrections require investigation. The spatial and temporal variability of these atmospheric constituents makes correction difficult on a global basis. Common correction approaches may only be possible on a continent by continent basis.

(v) *Alternative spectral indices.* There have been investigations of soil-adjusted vegetation indices (e.g., Huete 1989, Major *et al.* 1990). Soil differences can influence NDVI through AVHRR channel 1, with the problem worse near nadir, and so research should be pursued in this area in the future.

(vi) *Resampling.* Efforts should continue to identify the effects of resampling data between projections and to quantify the impact of radiometric deterioration due to resampling on the quality of the data.

5. Availability of Current AVHRR 1 km Data and the Feasibility of Coordinating Global Coverage

5.1 Introduction

This section summarizes the current availability of data with 1.1 km resolution from the Advanced Very High Resolution Radiometer (AVHRR) and recommends a strategy to achieve global acquisition and archiving. Digital 1 km resolution data acquired by the AVHRR sensor are transmitted to the ground in two modes. Local Area Coverage (LAC) data are recorded on board the satellite for selected portions of each orbit and played back when in range of the two Command and Data Acquisition (CDA) stations located at Wallops Island, Virginia and Fairbanks, Alaska. There is insufficient tape-recorder capacity on board the NOAA satellites to provide daily global LAC coverage, but High Resolution Picture Transmission (HRPT) 1 km data are continuously transmitted to ground in real time for reception by any ground station within direct line-of-sight.

5.2 Status of LAC Data

LAC data acquisitions are limited by a combination of tape-recorder capacity and playback time. Only 10-12 minutes from each orbit of approximately 100 minutes can be recorded. Playback time is limited to the time that the satellite is in range of the two CDA stations. Currently, the limited playback time available for the two CDA stations at Wallops Island and Fairbanks poses a greater limitation to LAC data acquisition than does the on-board tape recorder capacity. An additional CDA station exists at Lannion, France, but is not used for recorder playback of LAC data. Because of these limitations, scheduling and recording of LAC data must be carefully coordinated and managed.

The Interactive Processing Branch (IPB) of the National Environmental Satellite Data and Information Service (NESDIS) is responsible for the overall coordination of LAC scheduling. IPB processes incoming requests and coordinates the implementation of them with personnel in the NESDIS Satellite Operations Control Center (SOCC). LAC requests are scheduled on a first-come, first-served basis, according to the following priorities:

(i) National emergencies
(ii) Situations where human life is in immediate danger
(iii) US strategic requirements (e.g., Department of Defense)
(iv) Commercial requirements and US non-strategic requirements
(v) Scientific investigations and studies
(vi) Other miscellaneous activities.

Since requests based on priorities 1 and 2 cannot be planned, requests based on priorities 3 to 6 may be replaced when the need arises to schedule higher priority requests. Historically, LAC data acquisitions have not been guided by any considerations for periodic global land coverage.

Following the play-back of AVHRR LAC data to the CDA stations at Wallops Island, and Fairbanks, the data are then uplinked via a domestic communications satellite (Domsat) to the World Weather Building in Suitland, Maryland for archiving. Other Domsat antennae are capable of receiving the LAC data stream, including an operational antenna at the US Geological Survey's EROS Data Center (EDC). EDC has recorded the LAC data stream since June 1990 and has monitored all the daily LAC data acquisitions.

Observations over a period of several months indicate that about 40 LAC scenes are acquired per day by both the NOAA-10 and NOAA-11 satellites. Scenes range from 5 minutes to 11.5 minutes duration, with an average duration of about 9 minutes. The average scene duration of 9 minutes provides an along-track coverage on the ground of approximately 3900 km. Daily coverage of LAC scenes is typically as shown in Table 5.1.

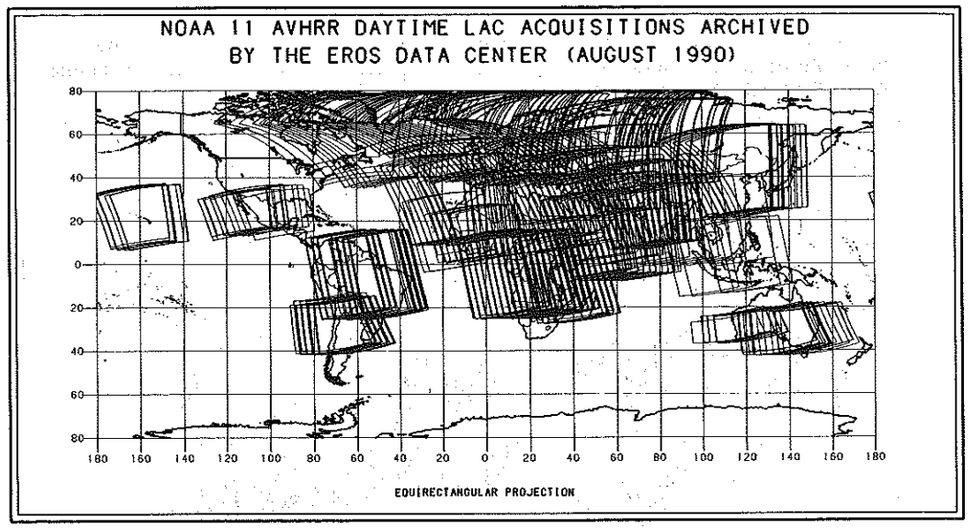
Table 5.1 Typical daily Local Area Coverage recorded on board NOAA-11.

Location	Number of Scenes Obtained
Hawaii	1
North America	6-7
Central America	1
South America	2-3
Greenland	3
Africa	6-7
Europe and West Asia	6-7
East Asia and Australia	8-10
Southern Hemisphere oceans	6-8

Figure 5.1 summarizes the land data acquisitions of NOAA-11 LAC data for the monthly periods of August 1990 and January 1991. These periods correspond to the respective summer seasons for the northern and southern hemispheres. Some of the seasonal variability is illustrated by a decrease in the frequency of coverage of the northern hemisphere land masses in January.

5.3 HRPT Data: Current Status

Numerous HRPT reception stations have been established around the world by government agencies, academic and research institutions, and private groups to serve a wide range of interests. Historically the HRPT stations have serviced the meteorological community. Capabilities and activities associated with acquiring and archiving data vary widely. Lack of international coordination among these stations has contributed to incomplete and inaccurate information about data acquisition and archiving policies and practices for each station. As part of the activities of the IGBP Land Cover Pilot Project recent efforts have attempted to acquire information on HRPT data acquisition and archive policies of ground stations around the world. Information has been gathered from the results of surveys, questionnaires and contacts with knowledgeable individuals. Major contributors of information include the NOAA/NESDIS, the European Space Agency's (ESA) Earthnet Programme Office, the US Geological Survey's EROS Data Center, the Global Inventory Monitoring and Modelling Studies (GIMMS) group at NASA/Goddard, and the CEC Joint Research Center at Ispra, Italy.



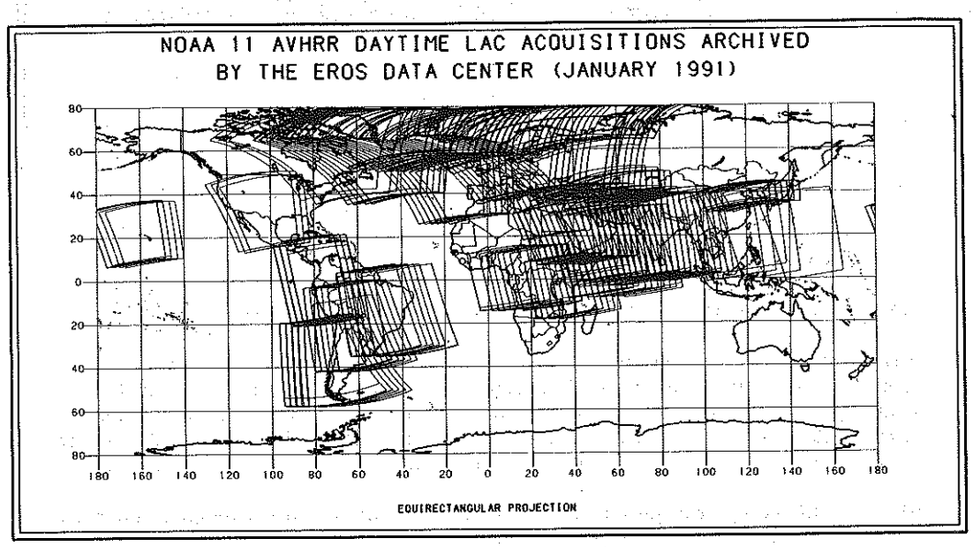


Fig. 5.1. Acquisitions of AVHRR data for one month using the satellite's tape-recording capabilities. (Upper) August 1990, (Lower) January 1991.

Figure 5.2 shows the approximate reception range for operational HRPT ground stations currently known to have a capability for digital archiving. Details on acquisition and archive policies for these stations are provided in Appendix 2. The distribution of stations in Figure 5.2 is based on the most recent information available to the authors about current operational archiving activities. The figure shows there are currently major gaps in the coverage of land areas by ground stations with digital archives in northern South America, Central and East Africa, the Middle East and a large part of Asia.

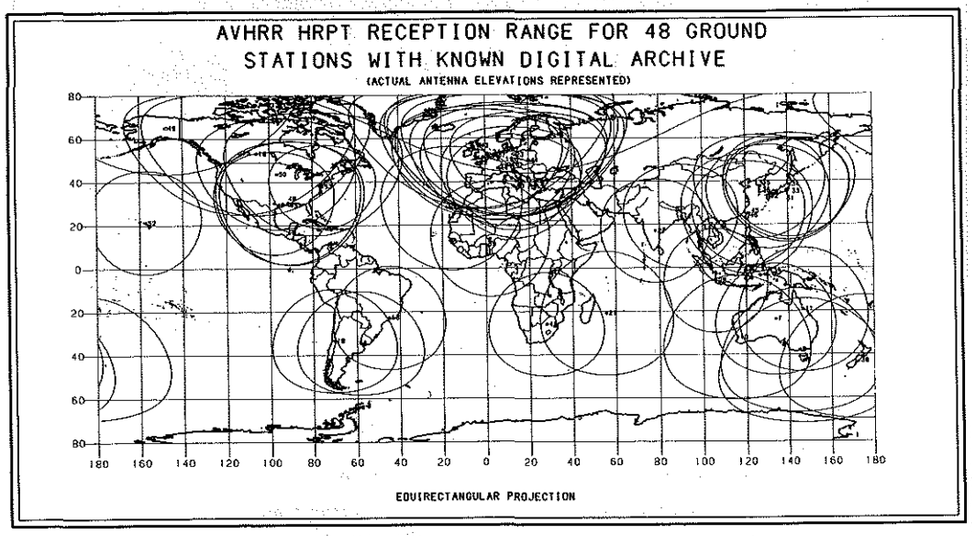


Fig. 5.2. Reception of AVHRR-HRPT stations with a digital archive (Antarctic stations not shown)

5.4 The Feasibility of Compiling a Global 1 km AVHRR Data Base

It is possible to assemble a comprehensive global archive of AVHRR 1 km data on a continuous basis by a combination of coverage from existing and currently planned HRPT ground stations and judicious use of the LAC on-board tape recorder. A selected number of HRPT stations could be organized to form a core network for this data collection effort. At this time, the major steps to achieve the compilation of a global 1 km data base are:

(i) coordinating the acquisition of LAC data by NOAA with the coverage obtained by a core network of HRPT ground stations

(ii) supporting the HRPT acquisition and digital archive operations of a few strategic ground stations where resources are currently inadequate to provide operational capability

iii) assembling the global archive (see Section 6.3).

5.5 Coordination of LAC and HRPT Data Acquisition

Because of the limited tape-recorder capacity on board the NOAA satellites, a concerted effort toward achieving a global 1 km data set must include HRPT ground stations willing to participate in a coordinated programme of data acquisition. A core network of ground stations should be established to provide the maximum global land coverage from a minimum number of reliable stations. An example of such a core network of HRPT stations is given in Fig. 5.3. This example of a global network assumes that the stations have the capability for archiving digital data at least for a few months of data at a time. Coordination of such a network of receiving stations could be facilitated by an international working group following the example of such fora as the Working Group on Data of the Committee for Earth Observation Satellites (CEOS), the Space Agency Forum for the International Space Year (SAFISY) or IGBP-DIS.

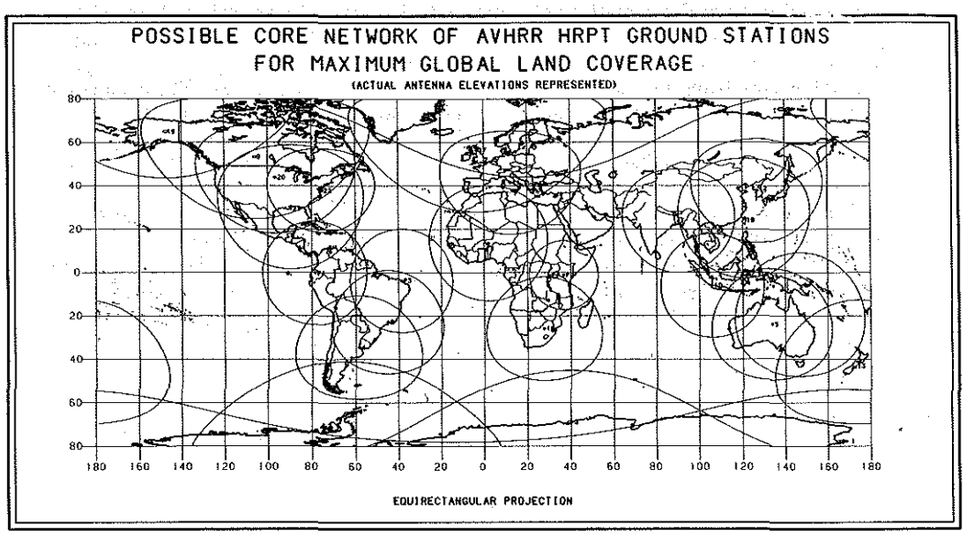


Fig. 5.3. One possible core network of AVHRR-HRPT stations for maximum global coverage

The USGS EROS Data Center has stated an interest in contributing to an international cooperative effort by exploring the logistics and developing the arrangements for establishing a core network. Some preliminary initiatives towards developing an AVHRR receiving station network are currently being made through the Earthnet Programme Office (EPO) of the European Space Agency. EPO is developing a digital archive from a network of ground stations in Europe and Africa and there are plans to incorporate data from three South American stations.

If a coordinated global network of operational ground stations can be established, and if data acquisition and archiving procedures are assured, it will be possible to prioritize the acquisition of LAC data to fill the gaps in the HRPT network coverage.

Such prioritizing could be initiated now to reduce tape-recorder use over areas for which HRPT data are presently assured and readily available. This would permit NESDIS to allocate LAC tape recorder time for other areas where HRPT data are currently unavailable. Preliminary correspondence with NOAA by IGBP-DIS has indicated willingness to support a global 1 km data collection initiative.

One immediate step toward increasing the capability for LAC data coverage would be to add the capability to playback LAC tape-recorded data to the CDA station at Lannion, France. This would increase the amount of playback time compared with that currently available from the two existing CDA stations in North America.

5.6 Supporting HRPT Data Acquisition and Archive Operations

Implementation of an optimal core network of HRPT ground stations will require efforts to install and support the operations of some strategic stations in countries where existing support is insufficient. ESA is at present contributing to a global network by installing additional HRPT stations which will cover some of the current gaps in global coverage. These stations are being installed in Forteleza, Brazil and Nairobi, Kenya. The installation of these stations is at an advanced stage and preliminary data collected by the Nairobi HRPT station are being evaluated by the ESA Earthnet Programme Office. A further station is planned for installation at Harare, Zimbabwe. In addition to new stations, there is a need to upgrade some existing HRPT stations to enable them to acquire and archive digital data on a continuous basis so they can reliably contribute to the global archive. Scientific incentives through IGBP might be sufficient to influence the improvement of national HRPT archive capabilities or facilitate data transfers from these stations to ensure the preservation of data at regional data centres. Alternatively some additional funding may be needed to support acquisition and archiving capabilities at selected stations.

6. Data Management

6.1 Introduction

The previous sections have discussed the scientific and technical aspects of the 1 km global data sets. A further crucial issue is the management of the data once they are collected. AVHRR data at 1 km resolution are at present read out in many regions for operational use such as weather analyses, but in most cases those who do receive the data have no provision for recording on long-term media and archiving the data for retrospective use. Some national and international agencies have archived 1 km AVHRR data for substantial areas (Appendix 2) notably ESA/ESRIN for both Europe and significant parts of Africa and the USGS EROS Data Center (Sioux Falls, South Dakota) for North America during the growing season (March through October) as well as increasingly large volumes of LAC data. Also some research groups in certain regions, who use the 1 km data for research or pilot operational products, have maintained an archive for several years. Examples include the University of Dundee and Freie Universitat Berlin which keep 1 km data for Europe; some 1 km data are kept for research uses for the Amazon region by INPE (São Jose dos Campos, Brazil), LERTS/CNES archive data for France and portions of West Africa.

These various regional and local efforts at data management are not themselves sufficient for the management of a global data base. In order to assure that we can make the global data sets available in a timely way, in agreed formats, on cost-effective and easy to use computer -readable media and through generally accessible data networking arrangements, it is also important to:

(i) disseminate information on the existence of the global data base and provide useful descriptions of the data appropriate for near-term use (Section 6.2)

(i) assure an appropriate archival mechanism for future use (Section 6.3)

(iii) agree upon distribution and archival media, and access software (Section 6.4).

6.2 Dissemination of Information on the Global Data Set and Modes of Access

At the first International Study Conference on IGBP Data in Moscow in August 1988, it was recommended that a directory for IGBP data should be established (IGBP 1988). At the Moscow Workshop, representatives of NASA and ESA reported on their work to build a directory structure and to agree on standard formats for describing the data entries. Since then the NASA Master Directory has become the pilot directory for IGBP, in collaboration with ESA, and also the Japanese and USSR space agencies along with other groups having extensive environmental data holdings. Given the development of this capability, it is logical that the prime source of information about the 1 km data set should be through the IGBP Directory. The goals of the IGBP Directory are to provide:

(i) a comprehensive high level listing and description of data sets useful for global change studies, including information on their content, the time period over which they were collected, their areal coverage, their time and space resolutions, the agency who holds the data and information on how to acquire the data

(ii) on-line access (including such mechanisms as e-mail, international networking, and telephone dial-up)

(iii) several full-access nodes around the world

(iv) alternate access through regularly up-dated hard copy and pc-versions on floppy disks.

The prototype Master Directory is now available at ESA/ESRIN, Frascati Italy; UNEP/GRID, Geneva; the EROS Data Center, Sioux Falls, SD; as well as NASA/GSFC.

6.3 Long-Term Archiving and Data Networking

6.3.1 General Archiving Policy

At the 17th ICSU General assembly in Athens in 1978 a resolution was adopted that all ICSU-approved programmes in geophysics and solar-terrestrial physics shall include data management plans for data collection, archiving and distribution, and that such plans will be developed in consultation with the ICSU Panel on World Data Centres. Since the International Geophysical Year (IGY) in 1957-58 and its offspring programmes, a World Data Center system has existed under ICSU auspices (ICSU 1989). In brief the ICSU WDC system consists at the moment of about 40 centres operated in various countries at national expense, but following the general principles and responsibilities as outlined in the ICSU Guide. Stimulated by the IGBP planning phase, one new center has been added to the ICSU WDC system, namely Soil Geography and Classification. The WMO system has added two new centres relevant to IGBP activities, namely the Global Runoff Center, Koblenz, Germany and the Greenhouse Gases Data Center, Tokyo, Japan.

In many past ICSU programmes, such as the IGY, the data collected were simply supplied to one of the World Data Centres (WDC), where they were kept safe and available for copying for users. In recent years, WDCs have expanded their data services, to include some aspects of processing usually developed in collaboration with scientific users.

In three recent major programmes, namely the Global Atmospheric Research Programme (GARP), the International Satellite Cloud Climatology Project (ISCCP) and the Tropical Oceans and Global Atmosphere programme (TOGA), observations and original data were sent to designated processing centres, usually operated by one of the collaborating research groups, where higher order processed data were derived. The latter included globally or regionally analyzed fields and lower resolution data derived from higher resolution data for modelling. After some use and quality control procedures by expert users, the final data products were (and are continuing to be) sent to WDCs for archiving and distribution.

WDC and other data systems could be encouraged to establish new disciplinary or multi-disciplinary data centres if IGBP expresses a general requirement.

In the context of the 1 km product, decisions will need to be made on the following:

(i) How and whether to use the existing WDC system (which is mainly discipline-oriented) to archive the basic 1 km AVHRR data product and/or for the products derived from them.

(ii) The extent to which individual IGBP Core Projects need to develop their own data archiving and distribution systems, for higher level products developed from the 1 km product

(iii) The relation of IGBP-DIS activities with other major archiving and distribution activities. For example, the recently formulated Global Climate Observing System (GCOS) is specifically planned to include a wide range of land as well as atmospheric and oceanic data sets.

6.3.2 Compiling the Global Archive

The task of long term archiving, if left to individual ground stations, will almost certainly result in a deficient system of data provision, resulting from varying policies affecting the conditions under which the data are archived and the accessibility of the data to the user community. Long term archiving responsibilities may also be an excessive burden for some of the operational receiving stations. An alternative approach would be to designate and support major regional data centres and a central global facility for the long term archive of AVHRR 1 km data. At the regional data centres, emphasis would be given to securing the continuous digital archive from a network of HRPT stations, establishing common formats for the data, and providing archive and distribution services to the science community. The World Data Centres of ICSU (Section 6.3.1) may provide a useful mechanism for maintaining the regional data archives and facilitating data distribution to the science community. At the global archive facility, emphasis would be on coordinating the compilation of LAC data acquired by NOAA and the necessary HRPT data from the regional data centres to assemble an efficient, long term archive of continuous global land coverage.

Complete global land coverage without any redundancy of AVHRR 1 km data for all 5 spectral channels is estimated to amount to approximately 3.0 gigabytes of data per day. This is a large, but manageable volume by today's standards. This amounts to about 1.08 terabytes annually.

Recent developments of data storage technology such as CD-ROMs and optical discs will greatly reduce the burden of archiving such large data volumes. Acquisition of night-time thermal data will involve acquiring and ingesting the same volume of data since the entire data stream must be taken. However, for archive purposes, the volume would decrease by two-fifths when data for the two shortwave bands are removed.

The global facility should provide indexing of all the meta-data of the global 1 km data in an advanced information system that would provide geographic query, interactive browse, and data ordering and distribution functions. In addition, the global facility should have the mission to produce periodic, spatially continuous data sets of geophysical parameters such as the NDVI for continental land masses.

The USGS EROS Data Center has stated its interest to host the global archive, provide the information system and produce derivative data products for the global change science community.

6.4 Distribution and Archival Media and Access Software

Many kinds of data media, ranging from hard copy to computer magnetic or optical media to direct electronic transfer, are used for the collection and processing of data and for intermediate exchange. New technologies are also making it possible to store and exchange data in very cost-effective ways to supplement older methods involving various hard copy media. There are a number of possible media whose characteristics are summarized in Table 6.1.

Table 6.1 Types of media, their advantages and disadvantages for remote sensing archiving

Media	Characteristics
Hard copy	These include tables, maps and photographic materials including microfilm. The main advantage of this medium is easy distribution, and ease of making casual, first inspection of the fields to find patterns or other interesting attributes. The main disadvantage lies in the inability of the user to manipulate the data. It is worth noting that hard copy, provided that the paper or film meets established archival standards, is the only class of media currently recognized for long term archiving.
Computer Tapes	Their advantages are ubiquitous access and use. Their main disadvantages are storage and shelf-life problems, serial search mode, cost of preparing and shipping.
Computer floppy diskettes	Their advantages are ubiquitous access and use, low cost, ease of copying and shipment, probable long-shelf life, and random search capability. Their main disadvantage is limited data volumes, although newer diskettes are now double density, i.e. about 2.4 Mbyte, and with packing for some kinds of data can hold about 5 Mbyte. Continuing progress is anticipated in storage capability.
CD-ROM	The advantages of CD-ROM are high storage capability, random access, long life, lower cost than competing media, such as tapes, for more than a few dozen copies and ease of distribution. Their disadvantages at the moment are limited distribution of readers, (but reduction of prices to the US $500 range should shortly alleviate this problem), and the relatively slow transfer speed for large files.
Slant-track (video) tape	Its advantages are low cost, high storage capability of several gigabytes. Disadvantages are slow search speed, the need for special readers and, at the moment, some loss of data after only a month or so due to tape stretching.
DAT and DAC	Digital Audio Tape (DAT) and Digital Audio Cassettes (DAC) are relatively new media and their use and characteristics have not yet been fully ascertained. However the tape medium itself is similar to conventional tapes, it is only the encoding that differs: thus we may expect similar advantages and disadvantages as discussed above for computer tapes but with much higher storage capacity.
Writable optical disks	Their advantages are high storage capability, and random access, qualities which make them particularly useful for unique data sets where only a few copies are needed. Disadvantages are the current lack of standardization, their high cost of reproduction, and the requirement for special high-cost readers.

Examination of this table indicates that there is an acceptable mix of media available, each with its own advantages and disadvantages. It is worth noting that except for hard-copy in the form of paper or film meeting archival standards, there are no other media yet acceptable, at least by US government agencies, for long term archiving in the absence of periodic renewal. Since technology continues to develop quickly, users of computer-readable media must be prepared to migrate to new products, since reading equipment may become obsolete and difficult to maintain.

In view of the fact that the CD-ROM music industry is a highly financed and growing enterprise, this medium provides at least one good prospect for medium term archiving, namely over a period of 10 to 20 years: however as mentioned above this medium will not fulfil all needs.

There are some considerable differences of opinion concerning the topic of access software. Some producers of high density data sets, such as those on CD-ROMs, believe they need only supply access software that transfers data to the users equipment. Other data suppliers have provided flexible access and manipulation software, notably where the data include images. Experience in the Global Change Database Project's Diskette Pilot Phase, is that good software makes the data much more accessible and interesting especially to new users, who then often add their own utilities to the system. One goal of the IGBP system could be to encourage the interchange and sharing of utility software, and IGBP-DIS could have the specific role of acting as a focus to provide porting of software from one computer system to another.

6.5 The Long-Term Perspective for A Global 1 km Archive

Global data of 1 km resolution will continue to be provided by the planned sensing systems of the NOAA AVHRR K, L, and M follow-on series, ESA's ATSR-2 (Along Track Scanning Radiometer-2), and NASA's Earth Observing System's MODIS (Moderate Resolution Imaging Spectrometer). The MODIS instrument as currently designed will acquire daily global data at 250 m, 500 m and 1 km resolution (Salomonson *et al.* 1989). Creation of a global AVHRR 1 km data base would provide a useful precursor for potential users of data from the MODIS instrument and an early start to a long term data base for the study of land cover change for IGBP and the global science community.

6.6 Broader Issues of Data Management

Consideration of the various issues raised in defining the AVHRR 1 km data set raises a number of generic issues relating to data management:

(i) The relationships between IGBP-DIS and various other activities such as the EOS-DIS, the World Data Center system and the Global Climate Observing System need to be established.

(ii) Mechanisms need to be established with key space agencies and major data suppliers such as the USGS in order to ensure that IGBP user requirements are properly represented through IGBP-DIS, so that AVHRR and other remote sensing data sets can properly support IGBP's activities.

(iii) The relative roles of Core Projects and IGBP-DIS in data management need to be established through consultations between these groups, and in particular through the mechanism of the IGBP-DIS Standing Committee.

7. Implementation of Proposals

7.1 Existing Coordination with Core Projects of IGBP

A preliminary version of this document was discussed with many members of several IGBP Core Projects at a workshop organized by IGBP-DIS in Toulouse in June 1991. The proposal for a 1 km data set was welcomed, firstly because of the need to create a global data set at this resolution for several requirements of Core Projects and secondly because it can provide the foundation for coarser resolution data sets for other applications without the disadvantages of the sampling and averaging scheme used to create Global Area Coverage (GAC) data (see Section 2.3 and Justice *et al.* 1989).

7.2 Actions Required by IGBP for Implementing Proposals

The full implementation of these proposals, such that an actual product is created and distributed to IGBP scientists in a timely fashion, is outside the scope of IGBP-DIS itself, given both its modest resources and its prime role of promoting the overall coordination of data handling and management within IGBP. The following recommendations are therefore made for actions by both the IGBP Scientific Committee and IGBP-DIS, in liaison with other bodies:

(1) The process of consultation with Core Projects concerning the character of the 1 km product, which was started in Toulouse, should be continued and extended through the activities of the IGBP-DIS Standing Committee and through the actions of members of IGBP-DIS who also are members of the Core Projects.

(2) The group of IGBP-DIS concerned with pre-processing (see Teillet 1990b) should urgently reach agreement on the pre-processing methods to be recommended for the product, as discussed in Section 4. In particular, decisions need to be finalized on the algorithms adopted for atmospheric correction and cloud recognition. So far as is compatible with IGBP objectives, these recommendations should take cognizance of the procedures which are being adopted in other major activities for the production of AVHRR products such as the joint NASA/NOAA Pathfinder project for a global 9 km data set, and other large area efforts such as those being initiated by the EROS Data Center, the Canada Centre for Remote Sensing, and the Joint Research Center, Ispra.

(3) The IGBP-DIS should initiate a joint meeting with the supervising authorities of AVHRR ground station operators and digital data archives, to gain agreement on the operational, continuing receipt and archiving of 1 km AVHRR data for the whole globe. The initial actions for this recommendation could well be carried out through interactions of IGBP-DIS with CEOS.

(4) IGBP-DIS should make every effort to ensure that at least one center is identified which will create a unified global archive and which will distribute the data set at minimal cost related only to the cost of the media. If more than one center wishes

to be involved in the production of such an archive, and in the distribution of products from it, IGBP-DIS should ensure that, as far as possible, the archives and distributed data sets are identical.

(5) When recommendations (2) - (4) are satisfactorily achieved, IGBP-DIS should then take a continuing role with respect to the 1 km data set. Among the activities for which a proactive role will be required are the following:

(i) There should be continuing liaison with respect to recommendations (2) - (4) to ensure that data are processed, archived and distributed to help fulfil IGBP's scientific goals.

(ii) Participation is required in quality assessment and development of applications.

(iii) An active role should be taken in the creation of manuals describing the product and its applications.

(iv) Information about the product should be disseminated and training in its use should be encouraged through activities such as seminars and workshops.

(v) The performance of the data set as part of IGBP's scientific activities should be monitored, and the findings should be used to develop improved versions of future data sets.

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Appendix 1: Proposed Implementation of a Surface Reflectance Retrieval Algorithm

The main objective of radiometric correction in this context is to obtain vegetation indices such as NDVI from surface reflectances rather than from the digital signal levels recorded at the sensor. The NDVI will then no longer be subject to changes in sensor calibration with time and from sensor to sensor, or to variations in illumination and observation geometries and atmospheric conditions. For application to regional and global data sets, the corrections must be fast and relatively straightforward.

The overall correction scheme (Fig 4.1) consists of calibrating digital signal levels to apparent radiance at the sensor and then correcting to surface reflectance taking atmospheric, illumination and view angle effects into account. The radiometric calibration to radiance is accomplished by means of the following equation:

$$L^*_i = (D_i - O_i)/G_i \qquad (1)$$

where L^* = radiance (W m^{-2} sr^{-1} μm^{-1}), D = digital signal level (counts), O = calibration offset coefficient (counts), G = calibration gain coefficient (counts/(W m^{-2} sr^{-1} μm^{-1})), and the subscript i refers to channel number (1 or 2). Significant degradations in responsivity have occurred for the AVHRR sensors since their prelaunch calibration and with time since launch (Brest and Rossow 1991, Holben *et al.* 1990, Teillet *et al.* 1990), so the coefficients G_i and O_i should be specified as a function of time since launch for each AVHRR sensor.

A semi-analytical but reasonably accurate atmospheric code that lends itself well to surface reflectance retrieval in this situation is the 5S code developed in France (Tanre *et al.* 1986, Tanre *et al.* 1990) and modified to facilitate reverse mode computations and include altitude dependence (Teillet 1989, Teillet 1991, Teillet and Santer 1991). In the 5S formulation, one can write the following expression for surface reflectance retrieval:

$$\rho_i = 100\, Y_i \,/\, (100 + Y_i S_i) \qquad (2)$$

where

$$Y_i = A_i\, d_s^2\, L^*_i + B_i$$

$$A_i = \frac{100\,\pi}{E_o \cos\theta_s\, \tau_g\, \tau_s\, \tau_v}$$

$$B_i = \frac{-100\,\rho_{atm}}{\tau_s\, \tau_v}$$

and ρ = surface reflectance (percent)
S = spherical albedo
τ_g = gas transmittance
τ_s = scattering transmittance in solar direction
τ_v = scattering transmittance in sensor direction
r_{atm} = atmospheric reflectance
d_s = solar distance in AU
E_o = exo-atmospheric solar irradiance (W m^{-2} μm^{-1}),
θ_s = solar zenith angle (degrees).

The spherical albedo S_i and the quantities necessary to calculate A_i and B_i can be obtained by running the 5S code. However, even though the code runs in a matter of seconds, it is not practical or necessary to run it for every pixel in the scene. On a production system, it is also impractical to use and maintain an atmospheric code. An alternative is to generate look-up tables (LUTs) for A_i, B_i, and S_i encompassing a range of possible illumination and observation geometries and assumed atmospheric conditions. The operational system can obtain values for A_i, B_i, and S_i from the LUTs at coarse grid locations in a given image. Each image block bounded by four grid locations can be fitted by bilinear functions that can then be rapidly evaluated for the correction of individual pixels. The solar distance factor d_s, will be constant for a given scene. This block-based approach is a two-dimensional equivalent of a piecewise linear approximation. Thus, the data flow for radiometric image correction is similar to commonly used geometric correction procedures.

Just as for the geometric correction process, two levels of terrain correction for radiometric effects are envisaged. The first-order correction is intended to take into account gross changes in terrain elevation that will cause variations in the scattering and absorption transmittances of the atmosphere. This is analogous to the first-order geometric terrain correction to a common geoid across the country. Such corrections are possible anywhere with currently available digital elevation models. Pixel-specific terrain corrections for localized radiometric and atmospheric effects (such as slope-aspect effects, for example) require highly accurate and very well-registered elevation data. This is analogous to the terrain relief correction for parallax effects on individual pixel locations, although the accuracy requirements for the digital terrain model are more stringent in the case of slope-aspect correction

Appendix 2: AVHRR HRPT Ground Stations with a Digital Archive

The following tables provide information on the location of AVHRR HRPT stations with a known digital archive. Information is provided on the acquisition and archiving policies of these stations. Current addresses and telephone/fax numbers are also given. The information provided is believed to be correct at the time of original compilation (April 1991). Inevitably changes in many of the details of this listing will occur with time.

See Section 5 for more information on the acquisition of AVHRR data with maps showing the coverage of the stations.

APPENDIX 2

SITE NAME	SITE LOCATION	ADDRESS	ACQUISITION			ARCHIVE				COMMENTS
			SATELLITE NUMBER	OVERPASS TAKEN D=DAY N=NIGHT	FREQUENCY D=DAILY S=SPORADIC	DATA ARCHIVED R=RAW P=PROCESSED	MONTHS RETAINED 999= PERMANENT	OPEN CATALOG? Y,N,U	DATA RETRIEVABLE? Y,N,U	
RALIA, E SPRINGS	LAT: 23 deg 45'S LONG:133 deg 52'E	ROBIN BUCKELY AUSTRALIAN CENTRE FOR REMOTE SENSING (ACRES) P.O. BOX 28 BELCONNEN ACT 2616, AUSTRALIA FAX: +61 6 252 4402 TELEX: +61 6 251 6326 AA 61510 ACRES C:AUSTRALIA, PUB:TELEMEMO, O:ACRES, UN:ROBIN.BUCKLEY	10-12	D	D	R	999	Y	Y	ARCHIVE SINCE 1ST Feb-89
RALIA, ART, MANIA	LAT: 42.48 deg S LONG:147.18 deg E	DR. CARL HILSSON CSIRO MARINE LABORATORIES PO BOX 1538 HOBART TASMANIA 7001 AUSTRALIA PHONE: +61 (002)206251 TELEX: AA 57182 FAX: +61 (002)240530	7-12	D + N	D	R	999	Y	Y	PAUL TILDESLEY PHONE: 6102 206251 FAX: 6102 240 530 NOAA 7-11 ARCHIVE SINCE 4/86 ALL BANDS
TRALIA, ENDALE	LAT: 38 deg S LONG: 145 deg E	ALEXANDER C. DILLEY CSIRO DIV. OF ATMOS. RESEARCH PRIVATE BAG NO 1, MORDIALLOC VICTORIA 3195, AUSTRALIA PHONE: +61 (03)586-7675 TELEX: AA34463 FAX: +61 (03)5867600	7-12		D	R	999	Y	Y	ALL BANDS ARCHIVE SINCE 3/84
TRALIA, TH	LAT: 32 deg O'S LONG:115 deg 53'E	MR. HENRY HOUGHTON WESTERN AUSTRALIA SATELLITE TECHNOLOGY AND APPLICATIONS CONSORTIUM (WASTAC) REMOTE SENSING APPLICATIONS CENTRE, 8TH FLOOR, JARDINE HOUSE,184 ST. GEORGE'S TERRACE PERTH, WESTERN AUSTRALIA 6000 PHONE: 619-323-1520/FAX 321-8576	7-12	D	D	R	999	Y	Y HARD COPY	ARCHIVE SINCE 1/1/81. HARD COPY CATALOG ONLY

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			SATELLITE NUMBER	OVERPASS TAKEN D=DAY N=NIGHT	FREQUENCY D=DAILY S=SPORADIC	DATA ARCHIVED R=RAW P=PROCESSED	MONTHS RETAINED 999= PERMANENT	OPEN CATALOG? Y,N,U	DATA RETRIEVABLE? Y,N,U	
ARCTICA, WA	AAT: 69 δεγ Σ LONG: 39 deg 34'E	NATIONAL INSTITUTE OF POLAR RESEARCH, TAKASHI, YAMANOUCHI 1-9-10 KAGA, ITABASHI-KU TOKYO, 173 JAPAN PHONE: +81 3962-4711 FAX: +81 3962-2529 TELEX: 272 3 515 POLRSC J	6-7 9-12	D	D	R+P	999	Y	Y	ARCHIVE SINCE 1/1/87
TARCTICA, RANOVA BAY	LAT: 74 deg 24'S LONG: 164 deg 07'E	ROBERTO CERVELLATI PNRA ENEA-CRE CASACCIA PAS S.P. AN GUILLARESE 301 00060 S.M. di GALERIA, ROMA, ITALY FAX: +39 6 3048 4893	10-12	D+N	D	R	999	Y	Y	GOOD DATA DURING SUMMER MONTHS ONLY
TARCTICA, IGGINS	LAT: 63 deg19'S LONG: 57 deg 54'W	KLAUS REINIGGER DLR 8031 OBERPFAFFENHOFEN GERMANY FAX: +49 815328 1443	9-12	D	S	R	999	Y	Y	FOUR SHORT PERIOD CAMPAIGNS PER YEAR, 4 TO 6 WEEKS EACH
TARCTICA, EMURDO STATION GENCY: ANTARCTIC SEARCH CENTER RIPPS CEANOGRAPHIC STITUTE	LAT: 77 deg 50'56"S LONG:166 deg 39'36"E	ROBERT WHRITNER SCRIPPS INST. OCEANOGRAPHY ANTARCTIC RESEARCH CENTER OCEAN RES. DIV., A-014 LAJOLLA, CA 92093, USA PHONE: (619) 534-3785 FAX: (619) 534-7383	6-11	D	D	R	999	Y	Y	8X10 REDUCED QUICK LOOK, ARCHIVE SINCE 10/85 ALL BANDS
NTARCTICA, ALMER STATION GENCY: RESEARCH NTARCTIC CENTER, CRIPPS CEANOGRAPHIC NSTITUTE	LAT: 64 deg 46'30"S LONG: 64 deg 04'00"W	ROBERT WHRITNER SCRIPPS INST. OCEANOGRAPHY ANTARCTIC RESEARCH CENTER OCEAN RES. DIV., A-014 LAJOLLA, CA 92093, USA PHONE: (619) 534-3785 FAX: (619) 534-7383	6-11	D	D	R	999	Y	Y	8X10 REDUCED QUICK LOOK, ARCHIVE SINCE 6/89, ALL BANDS
ARGENTINA, BUENOS AIRES	LAT: 34 deg 24'S LONG: 58 deg 18'W	SALVADOR ALAIMO SERVICIO METEROLOGICO NACIONAL 25 DE MAYO 658 BUENOS AIRES, ARGENTINA	11	D	D	R	UNCERTAIN	UNCERTAIN	UNCERTAIN	DATA ARCHIVED IN A RAW TELEMETRY FORMAT- REQUIRE CONVERSION TO CCT.

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			SATELLITE NUMBER	OVERPASS TAKEN D=DAY N=NIGHT	FREQUENCY D=DAILY S=SPORADIC	DATA ARCHIVED R=RAW P=PROCESSED	MONTHS RETAINED 999= PERMANENT	OPEN CATALOG? Y,N,U	DATA RETRIEVABLE? Y,N,U	
RALIA, NSVILLE	LAT: 19 deg18'S LONG:146 deg 48'E	JOHN LILLEYMAN NORTH-EAST AUSTRALIAN SATELLITE IMAGERY SYSTEM DEPT. OF ELECTRICAL AND ELECTRONIC ENGINEERING JAMES COOK UNIV. OF NORTH QUEENSLAND, TOWNSVILLE, QUEENSLAND, 4811 AUSTRALIA FAX: +61-77-251348 PHONE: 61-77-814379, TELEX: 47009	9-12	D + N	D	R	12	Y	Y	ACQUIRE 1-2 PASSES WEEKLY PRE-12/89, ALL PASSES POST12/89 ARCHIVED SINCE 1ST APRIL 88 DIGITAL BROWSE
GLADESH, KKA	LAT: 23 deg 45'N LONG: 90 deg18'E	A.M. CHOUDHURY BANGLADESH SPACE RESEARCH AND REMOTE SENSING ORGANIZATION (SPARRSO) AGARGAN, SHER-E-BANGLA NAGAR, DHAKA-1207 327335,	6-12	D + N	D	R + P	999	N	N	ARCHIVE HARDCOPY SINCE 1982, SELECT DIGITAL SINCE 1985
IL, IOEIRA PAULISTA	LAT: 22 deg 45'S LONG: 45 deg 00'W	642 215 SRS BJ SERGIO DE PAULA PEREIA INSTITUTO DE PESQUISAS ESPACIAS (DEPARTMENT OF OPERATIONS) RODOVIA PRESIDENTE DUTRA KM 40/SP, CP 001 12630 CACHOEIRA PAULISTA, SAO PAULO, BRASIL PHONE: +55 125 61 1377 FAX: +55 125 61 2088	9-12	D + N	S	R	999	N	Y	ARCHIVE SINCE 1ST JUNE 89;1 PASS JUNE TO OCT. N-9/11 CH.1-3; 3 PASSES WEEKLY NOV to MAY N-9/11 CH. 1-2
ADA, NSVIEW, ARIO	LAT: 43 deg 46'N LONG: 79 deg 28'W	MR. A. ALDUNATE ATMOSPHERIC ENVIRONMENT SERVICE SATELLITE DATA LAB 4905 DUFFERIN STREET DOWNSVIEW, ONTARIO CANADA M3H 5T4 PHONE: 416-739-4896/FAX 416-739-4521	9-11	D	D	R + P	10 YEARS	Y	U	DAILY PASS OVER EASTERN CANADA IS SENT TO CCRS FOR ARCHIVE. LIMITED ARCHIVE FOR RESEARCH

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			SATELLITE NUMBER	OVERPASS TAKEN D=DAY N=NIGHT	FREQUENCY D=DAILY S=SPORADIC	DATA ARCHIVED R=RAW P=PROCESSED	MONTHS RETAINED 999= PERMANENT	OPEN CATALOG? Y,N,U	DATA RETRIEVABLE? Y,N,U	
ADA, ONTON, RTA	LAT: 53 deg 30'N LONG:113 deg 30'W	RON GOODSON ATMOSPHERIC ENVIRONMENT SERVICE, WESTERN REGION FORECAST OPERATIONS EDMONTON, ALBERTA CANADA PHONE: 403-468-7910 FAX: 403-468-7916	10 + 11		D	R + P	10 DAYS OR 24 MO. HARDCOPY	N	?	10 DAY ROTATING FOR DIGITAL 1 YEAR HARDCOPY
ADA, CE ALBERT, ATCHEWAN	LAT: 53 deg12'N LONG:105 deg 55'W	IAN PRESS MR. LEON BRONSTEIN CANADA CENTER FOR REMOTE SENSING, 2464 SHEFFIELD RD, OTTAWA, ONTARIO K1A 0Y7 CANADA PHONE: 613-991-5505 FAX: 613-952-9089 TELEX: 053-3589	6-12	D	D	R	999	Y	Y	ARCHIVE 7/83
ARY ISLANDS, PALOMAS	LAT: 27 deg 46'N LONG:15 deg 37'W	MANOLO SOZA ESTACION ESPACIAL DE MASPALOMAS LAS PALOMAS DE GRAN CANARIA P.O. BOX 29 MASPALOMAS, SPAIN PHONE: +34 28 761 876 FAX: +34 928 766 956	9-12	D	D	R	999	Y	Y	ARCHIVE SINCE 1ST JUL 86 AT GRAN CANARIA, SPAIN
E, SANTIAGO	LAT: 33 deg18'S LONG: 70 deg 24'W	RAMON L. MOLINA CENTRO DE ESTUDIOS ESPACIALES, UNIVERSIDAD DE CHILE CASILLA 411-3 SANTIAGO, CHILE PHONE: +56 2 721 816 FAX: +56 2 844 1003	7-12	D + N	D	R	999	Y	N	ARCHIVE SINCE 1ST NOV. 83
CHOSLOVAKIA, GUE	LAT: 50 deg 04'N LONG:14 deg 27'E	MARTIN SETVAK & STEPAN KYJOVSKY CZECH HYDROMETEOROLOGICAL INSTITUT, PRAGUE CHMI, OBSERVATORY LIBUS NA SABATCE 17 143 06 PRAGUE 4, CZECHOSLOVAKIA PHONE: +42 2 468380, FAX: +42 2 4010800	6-12			R		Y	Y	SELECTED DATA FOR METEROLOGICAL RESEARCH

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			SATELLITE NUMBER	OVERPASS TAKEN D=DAY N=NIGHT	FREQUENCY D=DAILY S=SPORADIC	DATA ARCHIVED R=RAW P=PROCESSED	MONTHS RETAINED 999= PERMANENT	OPEN CATALOG? Y,N,U	DATA RETRIEVABLE? Y,N,U	
ICE, LANNION	LAT: 48 deg 45'N LONG: 03 deg 28'W	PASCAL BRUNEL CENTRE DE METEOROLOGIE SPATIALE, BP 147 22302 LANNION CEDEX, FRANCE PHONE: +33 96 05 67 45 FAX: +33 96 05 67 37	6-12	D + N	S	R + P	25 MONTH ROLLING	Y	Y	ACQUIRE DATA WITH EQUATOR CROSSING 20W-40E ASC. OR 150W-140E DES.
MANY, BERLIN	LAT: 52 deg 28'N LONG:13 deg 12'E	FREE INSTITUTE OF BERLIN INST. OF METEOROLOGY, FB 24/WE7 ATTN: DIRK KOSLOWSKY DIETRICH-SCHAEFER-WEG 6 D-1000, BERLIN 41 FEDERAL REPUBLIC OF GERMANY FAX: +49 30 838 3874	6-11	D + N	D	R + P	999	N	Y	ARCHIVE SINCE 1ST Sep-88
MANY, MERHAVEN	LAT: 53 deg 31'N LONG: 08 deg 34'E	ALFRED WEGENER INSTITUTE FOR POLAR UND MEERESFORSCHUNG AM HANDELSHAFEN 12 D-2850 BREMERHAVEN, GERMANY PHONE: +49 471 483 1523 +49 471 483 1425 238 695 POLAR D ALFRED.WEGENER OR PIPOR.OFFICE	9-12		S	R + P		N	Y	SHORT PERIOD SCIENTIFIC CAMPAIGNS SINCE 1st APRIL 88
MANY, IBURG	LAT: 53 deg 34'N LONG: 09 deg 58'E	RAINER FUDLOGG BSH, BERNHARD NOCHT STR. 78 D-2000 HAMBURG 36 POSTFACH 301220 D-2000 HAMBURG 36 PHONE: +49 40 3190 5125 FAX: +49 40 3190 5150 TELEX: 2 11 138 BSH HH D	9-12		D	R		Y	U	ARCHIVE SINCE 12/89
MANY, RPFAFFENHOFEN NICH)	LAT: 48 deg 30'N LONG:11 deg 09'E	WALTER EBKE DLR 8031 OBERPFAFFENHOFEN GERMANY PHONE: +49 8153 28 1187 FAX: +49 8513 28 1443	6-12	D + N	D	R	999	Y	Y	PRE-1983 LIMITED ARCHIVE ONE PASS DAILY 1983-86

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A, DNAGAR, ERABAD	LAT:17 deg 07'N LONG: 78 deg 20'E	PROF. B.L. DEEKSHATULU DIRECTOR, NRSA BALANAGAR HYDERABAD 500 037 INDIA	11	D + N	D	R	999			DATA ARCHIVED ON HDDT SINCE 31ST JAN 87.
Y, IA	LAT: 41 deg 26'N LONG: 12 deg 16'E	PAOLO PAGANO SERVIZIO METEOROLOGICO DELL' AERONAUTICA, PIAZZALE DEGLI ARCHIVI, 34, 00144 ROMA, ITALY PHONE: +39 6 5996 410 FAX: +39 6 5920 994	9-12	D	D	R		N	N	TIP EVERY PASS, SOMETIMES AVHRR, ARCHIVE SINCE 1ST NOV 89
Y, NZANO	LAT: 37 deg 54'N LONG: 13 deg 21'E	SANDRO AND DEPISCOPO, ENNIO RICCOTTILLI, TELESPAZIO VIA TIBURTINA 965 00156 ROMA, ITALY PHONE: +39 6 4069 3375	9-12		D	R		Y	U	START ACQUISITIONS 1/1/91
ONESIA, PAN	LAT: 6 deg S LONG: 106 deg E	TEJASUKMANA BAMBANG SBSCL LAPAN J1 KALISARI PEKAYON JAKARTA TIMUR, INDONESIA PHONE: +62 21 8710065 FAX: +62 21 8710786	6-12	D	D	R	999	N	Y	ARCHIVE INDONESIA AREA SINCE 1/1/1981
AN, OSE	LAT: 35 deg 45'N LONG: 139 deg 31'E	SEI-ICHI SAITOH METEOROLOGICAL INFORMATION CENTER, JAPAN WEATHER ASSOCIATION 5, 4-CHOME, KOUJIMACHI, CHIYODA-KU TOKYO, JAPAN PHONE: +81 3 238 0480 FAX: +81 3 262 9549	6-12	D	D	R + P	999	Y	Y	ARCHIVE SINCE 1ST MAR 87 (JAPAN ISLAND)

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AN, YO AI UNIVERSITY	LAT: 32 deg 49'N LONG:130 deg 52'E	HARUHISA SHIMODA TOKAI UNIVERSITY RESEARCH AND INFORMATION CENTER (TRIC) 2-28-4 TOMIGAY, SHIBUYA-KU TOKYO, 151, JAPAN PHONE: +81 03 481 0611 FAX: +81 03 481 0610	6-12	D	D	R + P	999	N	Y	ARCHIVE SINCE IST APR 87
AN, YO YO UNIVERSITY	LAT: 36 deg N LONG: 140 deg E	MIKIO TAKAGI INSTITUTE OF INDUSTRIAL SCIENCE UNIVERSITY OF TOKYO 7-22-1, ROPPONGI MINATO-KU (CNPR) TOKYO, 106, JAPAN PHONE: +81 3 479 0289 FAX: +81 3 402 6226	6-12	D	D	R	999	Y	Y	ARCHIVE SINCE 26 Jan-83
AN, DAI	LAT: 38 deg 15'N LONG:140 deg 50'E	DR. HIROSHI KAWAMURA EARTH OBSERVING SATELLITE CENTER, CENTER FOR ATMOS. AND OCEANIC VAR., FACILITY OF SCIENCE, TOHOKU UNIVERSITY, SENDAI 980, JAPAN PHONE: +81 22 222 1800 X3346 FAX: +81 22 268 2179	9-12	D	D	R + P	999	Y	Y	ARCHIVE SINCE 4/1/88 PROCESSED CH 2+4 OF TOHOKU AREA
REA, UL: KMS	LAT: 37 deg 36'N LONG: 127 deg 00'E	CHOI, HEE SEUNG SATELLITE METEOROLOGY DEPARTMENT, KOREA, METEOROLOGICAL SERVICE 1, SONGWOL-DONG, CHONGNO-GU SEOUL 110-101, KOREA PHONE: +82 2 737 0011 FAX: +82 2 737 0325 27276 KMSSEL K	10-12	D + N	D	P	999	Y	Y	ARCHIVE SINCE 6/20/89 OF GOOD QUALITY

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REA, UL TIONAL IVERSITY	LAT: 37 deg 30'N LONG: 127 deg E	CGYBGM HIBG YUI REMOTE SENSING AND IMAGE PROCESSING LAB DEPARTMENT OF OCEANOGRAPHY, SEOUL NATIONAL UNIVERSITY SOEL 151-742, KOREA PHONE: +82 2 880 6747 FAX: +82 2 882 4216 29664 SNUROK K	9-12	D	D	R	999	Y	Y	ARCHIVE SINCE 11/25/89 ALL ACQUIRED PASSES
REUNION	LAT: 20 deg 52'S LONG: 55 deg 28'E	MICHEL PETIT CENTRE ORSTOM 2051, AVENUE DU VAL DE MONTERRAND 34032 MONTPELIER, FRANCE PHONE: +33 67 617 445 FAX: +33 67 547 800	9-12	D	D	R	999	Y	Y	ARCHIVE SINCE 12/15/89 AT LA REUNION, FRANCE ONE IMAGE DAILY
GER, AMEY	LAT: 13 deg 31'N LONG: 02 deg 04'E	NIAMEY FIELD OFFICE CENTRE AGRHYMET FAX: 011 227 732435 TELEX: 011 982 5448 NI	10-12	D	D	R + P	999	Y	Y	ARCHIVE SINCE IST MAY 89 AT NIAMEY (NDVI) OR FRASCATI
ETHERLANDS, E BILT	LAT: 52 deg N LONG: 05 deg E	JAN R. BIJMA P.O. BOX 201 3730 KONINGIN WILHELMINALAAN 10, DE BILT, NETHERLANDS PHONE: +31 30 206 435 FAX: +31 30 210 407 TELEX: 47096 KNMI NL	6-12	D	D	P	999	Y	Y	ARCHIVE SINCE IST FEB 90 (CLOUD FREE)
EW ZEALAND, ELLINGTON	LAT: 41 deg 12'S LONG: 174 deg 30'E	DEPT. OF SCIENTIFIC AND INDUSTRIAL RESEARCH (D SIR) PRIVATE BAG PALMEISTON NORTH NEW ZEALAND FAX: 063-66-664	10-12	D	D	P GEO- LOCATED	999	N	N	ARCHIVE SELECTED ACQUISITION SINCE IST OCT1981

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RWAY, OMSO	LAT: 69 deg 39'N LONG: 18 deg 56'E	ROLF-TERJE ENOKSEN STATION MANAGER TROMSO TELEMETRY STATION P.O. BOX 387 N-9001 TROMSO, NORWAY	6-12	D + N	D	R	999	Y	Y	DATA ACQUISITION SINCE 1/84. DATA ARE SENT TO ESA-EARTHNET FOR ARCHIVE. PRE 90=2 PASSES DAILY. POST 90= ALL PASSES ON OPTICAL DISC.
LAND, AKOW	LAT: 50 deg N LONG: 20 deg E	LESLAW BARANSKI INST. OF MET. AND WATER MANAGEMENT (SATELLITE CENTER), KRAKOW, PIOTRA BOROWEGO STR. 14 30-215 KARKOW, POLAND PHONE: +48 12 113 844 FAX: +48 12 116 798	9-12	D	D	R	999	N	Y	ARCHIVE SINCE 23 APRIL 87 GOOD QUALITY DATA
UTH AFRICA, RTEBBESTHOEK	LAT: 25 deg 53'S LONG: 27 deg 42'E	TIMOTHY BOYLE, MARAIS IKE SATELLITE APPLICATIONS CENTRE HARTEBEESTHOEK MIKOMTER/CSIR PO BOX 395 0001 PRETORIA, SOUTH AFRICA PHONE: +27 11 642 4693 FAX: +27 11 642 2446	6-12	D + N	D	R	999	Y	Y	ARCHIVE SINCE I NOV 84 AT HARTEBEESTHOEK
ITZERLAND, RNE	LAT: 46 deg10'N LONG: 06 deg 00'E	MICHAEL BAUMGARTNER GEOGRAPHIUSCHES INSTITUT DER UNIVERSITAT BERN HALLERSTRASSE 12 3012 BERNE, SWITZERLAND PHONE: +41 31 658 020 FAX: +41 31 658 511	6-12	D + N	D	R	999	Y	Y	ARCHIVE SINCE 1/1/81 CH. 2 & 4 SOMETIMES CH. 3
IWAN, ELUNG	LAT: 25 deg 07'N LONG: 121 deg 43'E	CHI-YUAN LIN TAIWAN FISHERIES RESEARCH INSTITUTE,199 HOU-IN ROAD KEELUNG 20220, TAIWAN PHONE: +886 2 462 2101 FAX: +886 2 462 9388	10-12	D + N	D	R	999	N	?	ARCHIVE SINCE IST APR 89 GOOD QUALITY

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			SATELLITE NUMBER	OVERPASS TAKEN D=DAY N=NIGHT	FREQUENCY D=DAILY S=SPORADIC	DATA ARCHIVED R=RAW P=PROCESSED	MONTHS RETAINED 999= PERMANENT	OPEN CATALOG? Y,N,U	DATA RETRIEVABLE? Y,N,U	
WAN, PEI	LAT: 25 deg N LONG: 121 deg E	TAI-CHUNG YEN METEOROLOGICAL SATELLITE CENTER, CENTRAL WEATHER BUREAU, 64 KUNG YUAN ROAD TAIPEI, TAIWAN PHONE: +886 2 371 3181 X701 FAX: +886 2 331 5915	6-12	D + N	D	R	999	N	N	ACQUISITION START 28-Jan-81
TED KINGDOM, NDEE	LAT: 56 deg 27'N LONG: 2 deg 30'W	PETER BAYLIS NERC SATELLITE STATION UNIVERSITY OF DUNDEE DUNDEE DD1 4HN, SCOTLAND PHONE: +44 382 23181 X4406 FAX: +44 382 202 830 76293 ULDUND G	6-12	D + N	D	R.	999	Y	Y	DATA ARCHIVED SINCE 6-Nov-78
TED KINGDOM, IIAM	LAT: 51 deg 11'N LONG: 01 deg 02'W	ANTHONY MILES SPACE DEPARTMENT, Y60H BUILDING, ROYAL AEROSPACE ESTABLISHED, FARNBOROUGH HAMPSHIRE GU14 6TD, ENGLAND PHONE: +44 252 2441 X5787 FAX: +44 252 375 329	6-12	D	D	R	2 WEEK 1991=LONG TERM	N	N	2 WEEK ROLLING-START ARCHIVE IN 1991
A, STIN, TX	LAT: 30 deg 16'N LONG: 97 deg 45'W	MELBA CRAWFORD, DIRECTOR CENTER FOR SPACE RESEARCH UNIVERSITY OF TEXAS AT AUSTIN AUSTIN, TEXAS 78712, USA PHONE: (512) 471-3070 FAX: 471-8727	10, 11	D	D	R	999	Y	Y	
A, TON ROUGE, LA	LAT: 30 deg 24'N LONG: 91 deg 10'W	DR. OSCAR HUH LOUISIANA STATE UNIVERSITY COASTAL STUDIES INSTITUTE 3RD FLOOR, OLD GEOLOGY BLDG. HOWE-RUSSELL GEOSCIENCE COMPLEX, BATON ROUGE, LA 70803-7527 , USA PHONE: (504) 388-2952 FAX: 388-2520	9,10,11	D + N	D	R	999	Y	Y	ARCHIVE SINCE 28 Jun-68

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A, IRBANKS, AK	LAT: 64 deg 58'N LONG: 147 deg 30'W	NOAA/NESDIS/NCDC SATELLITE DATA SERVICES DIV. ROOM 100 PRINCETON EXECUTIVE SQUARE 5627 ALLENTOWN ROAD WASHINGTON, D.C. 20233, USA PHONE: (301) 763-8400 ALASKA PHONE: (907) 474-7487 FAX: 763-8443	6-11	D + N	D	R	999	Y	Y	DATA UPLINKED VIA DOMSAT TO NOAA/ NESDIS IN SUITLAND, MARYLAND FOR ARCHIVE.
A, SNUG HARBOR, AWAII	LAT: 21 deg 19'N LONG: 157 deg 15'W	PIERRE FLAMENT DEPARTMENT OF OCEANOGRAPHY UNIVERSITY OF HAWAII AT MANOA 1000 POPE ROAD HONOLULU, HI 96822, USA	9-11		D	P	12 ON-LINE SST TO CD	Y	Y	ARCHIVE SINCE 1 JUN 90
A, OUX FALLS, SD	LAT: 43 deg 32'N LONG: 96 deg 44'W	EROS DATA CENTER CUSTOMER SERVICES SIOUX FALLS, SD 57198, USA PHONE: (605) 594-6507 FAX: 594-7589	9-11	D	D	R	999	Y	Y	ACQUISITION AND ARCHIVE SINCE MAY 87. BROWSE IMAGES ON MICROFICHE. DEVELO-PING DIGITAL BROWSE.
A, ENNIS SPACE NTER, MS	LAT: 30.12 deg N LONG: 89.33 deg W	ED ARTHUR NAVAL OCEAN & ATMOSPHERIC LAB (NOARL) CODE 321 STENNIS SPACE CENTER, MS 39529-5004, USA PHONE: 601-688-5265 FAX: (601) 688-4149	10-11		S	P	12	Y	Y	ARCHIVE = 1 YEAR ROLLING
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Acronyms

AET	Actual Evapotranspiration
AMSU	Advanced Microwave Sounding Unit
ATSR-2	Along Track Scanning Radiometer-2
AVHRR	Advanced Very High Resolution Radiometer
BAHC	Biospheric Aspects of the Hydrologic Cycle (IGBP)
CCRS	Canada Centre for Remote Sensing
CDA	Command and Data Acquisition
CEC	Commission of the European Community
CEOS	Committee for Earth Observation Satellites
CEOS	Committee on Earth Observation Satellites
CSIRO	Commonwealth Scientific and Industrial Research Organization
DAC	Digital Audio Cassette
DAT	Digital Audio Tape
DCW	Digital Chart of the World
DIS	Data and Information System (IGBP)
DN	Digital Number
DOMSAT	Domestic Communications Satellite
DVI	Difference Vegetation Index
EDC	EROS Data Center
EOS	Earth Observing System
EPO	Earthnet Programme Office
EROS	Earth Resources Observing Satellite
ERS	European Remote Sensing satellite
ESA	European Space Agency
FAO	Food and Agricultural Organization
GAC	Global Area Coverage
GAIM	Global Analysis Interpretation and Modelling (IGBP)
GARP	Global Atmospheric Research Programme
GCM	General Circulation Model
GCOS	Global Climate Observing System
GCTE	Global Change and Terrestrial Ecosystems (IGBP)
GIMMS	Global Inventory Monitoring and Modelling Studies
GSFC	Goddard Space Flight Centre
GVI	Global Vegetation Index
HRPT	High Resolution Picture Transmission
HRV	Haute Resolution Visible
ICSU	International Council of Scientific Unions
IFOV	Instantaneous Field of View
IGAC	International Global Atmospheric Chemistry Project(IGBP)
IGBP	International Geosphere-Biosphere Programme
IGY	International Geophysical Year
IPB	Interactive Processing Branch
ISCCP	International Satellite Cloud Climatology Project
ISLSCP	International Satellite Land Surface Climatology Project
ISY	International Space Year
JRC	Joint Research Center
LAC	Local Area Coverage
LANDSAT	Land Remote Sensing Satellite
LERTS	Laboratoire d'Etudes et de Recherches Télédétection Spatiale
LUT	Look-up Table

MERIS	European Medium Resolution Imaging Spectrometer
MODIS	Moderate Resolution Imaging Spectrometer
MSS	Multispectral Scanner System
MTV	Monitoring Tropical Vegetation
NAS	National Academy of Science (USA)
NASA	U.S. National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NDVI	Normalized Difference Vegetation Index
NESDIS	National Environmental Satellite Data and Information Service (USA)
NIR	Near Infrared
NOAA	National Oceanic and Atmospheric Administration
NPP	Net primary productivity
NRC	National Research Council (USA)
SAFISY	Space Agency Forum for the International Space Year
SMMR	Scanning Multifrequency Microwave Radiometer
SOCC	Satellite Operations Control Center
SPOT	Système pour l'Observation de la Terre
TM	Thematic Mapper
TOGA	Tropical Oceans and Global Atmosphere programme
TREES	Tropical Ecosystem Environment Observations by Satellite
USGS	U.S. Geological Survey
WDC	World Data Centre

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