THE ENHANCED NOAA GLOBAL LAND DATASET FROM THE ADVANCED VERY HIGH RESOLUTION RADIOMETER

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ABSTRACT

Global mapped data of reflected radiation in the visible (0.63 μm) and near-infrared (0.85 μm) wavebands of the Advanced Very High Resolution Radiometer on board NOAA satellites have been collected as the Global Vegetation Index (GVI) dataset since 1982. Its primary objective has been vegetation studies (hence its title) using the normalized difference vegetation index, NDVI, calculated from the visible and near-IR data. The second generation GVI, that started in April 1985, have also included brightness temperatures in the thermal IR (11 μm and 12 μm) and the associated observation-illumination geometry. This multi-year, multi-spectral, multi-satellite dataset is a unique tool for global land studies. At the same time, it raises challenging remote sensing and data management problems with respect to uniformity in time, enhancement of signal to noise ratio, retrieval of geophysical parameters from satellite radiances, and large data volumes. We explored a four-level generic structure of processing AVHRR data, the first two levels being remote sensing oriented and the other two directed at environmental studies, and will describe the present status of each level. The uniformity of GVI data was improved by applying an updated calibration, and noise was reduced by applying a more accurate cloud-screening procedure. In addition to the enhanced weekly data (recalibrated with appended quality/cloud flags), the available land environmental products include monthly 0.15°-resolution global maps of top-of-the-atmosphere visible and near-IR reflectances, NDVI, brightness temperatures and a precipitable water index for April 1985-September 1994. For the first time, a 5-year monthly climatology (means and standard deviations) of each quantity was produced. These products show strong potential for detecting and analyzing large-scale spatial and seasonal land variability. The data can also be used for educational purposes to illustrate the annual global dynamics of vegetation cover, albedo, temperature, and water vapor. Development of the GVI data product contributes to the activities of the International Geosphere-Biosphere Programme (IGBP) and Global Energy and Water Cycle Experiment (GEWEX), and, in particular, the International Land Surface Satellite Climatology Project (ISLSCP). Monthly standardized anomalies of the GVI variables have been calculated for April 1985-present and are routinely produced on UNIX workstations, thus providing a prototype land monitoring system. Standardized anomalies clearly indicate that strong signals at the land surface, such as droughts and floods, and their teleconnections with such global environmental phenomena as El Niño southern oscillation, can be detected and analyzed. The monitoring of relatively small year-to-year variability is, however, contingent on the removal of residual trends/noise in GVI data which are of the order of the analyzed effects.

1. INTRODUCTION

Climate studies require long-term sets of geographically referenced global land surface data to initialize and validate numerical models for the analysis of complex interactions and feedbacks within the earth system (IGBP 1992). Conventional ground observations cannot provide all the required information and must be supplemented from satellites. Another application of long-term global time series of satellite data is establishing climatologies of both top-of-the-atmosphere radiances and derived surface characteristics which could in turn be used as a baseline for monitoring climate-scale variability. Among the objectives of the International Geosphere-Biosphere Programme (IGBP), the Global Energy and Water Cycle Experiment (GEWEX) and, in particular, the International Land Surface Satellite Climatology Project (ISLSCP) is aggregation of long-term global datasets that will provide a better insight into land-atmosphere interaction on diverse scales.

The Advanced Very High Resolution Radiometer (AVHRR) on board NOAA satellites is most appropriate for the above applications due to availability of the spectral information for vegetation studies, operational global daily coverage, and long-term continuous observational period. Additionally, AVHRR data are readily available at a nominal cost, whereas the high resolution data from LANDSAT and SPOT are costly and cover only limited regions of the globe episodically.

Over 13 years of global AVHRR data have been archived at NOAA. Processing these data is a challenge for computational facilities, with navigation and mapping of the original data into a regular grid being the most computer intensive tasks. The huge volumes of satellite data require compression in space and time. Two global mapped AVHRR datasets over land have been aggregated by sampling those observations and mapping them into a regular grid, with further reduction of the data volume by temporal compositing that also reduces cloud contamination. They are the NASA Global Inventory Monitoring and Modelling Studies (GIMMS) and the NOAA Global Vegetation Index (GVI). Both are sampled AVHRR Global Area Coverage (GAC) data, mapped into regular grids, with each map cell being represented by a single GAC 4-km pixel. The GIMMS dataset, with a spatial resolution of about $(8\ \text{km})^2$, was produced on a continent-by-continent rather than globally-uniform basis and does not include all AVHRR channels (IGBP 1992). Although no complete documentation, such as a User's Guide, is available, this research dataset has been very useful for numerous studies (e.g. Tucker et al. 1985; Justice et al. 1985; Tucker et al. 1991; Los et al. 1994, and many others).

The NOAA GVI, produced on a globally uniform basis with a $(0.15°)^2$ resolution, is currently the most complete and documented global AVHRR dataset (IGBP 1992; Tarpley 1991; Goward et al. 1993; Gutman 1994a; Kidwell 1994). It has been primarily directed on studies of global vegetation distribution and dynamics, hence its title. Between 1982 and April 1985 measurements in only solar wavebands of AVHRR and their combination -- normalized difference vegetation index (NDVI) -- were archived as the first generation GVI product. Many vegetation studies have been based on NDVI data (e.g. Malingreau 1986; Gallo and Flesch 1989; Kogan 1990; Tateishi and Kajiwara 1991; Hastings and Di 1994). Since April 1985, measurements in thermal IR wavebands, and the associated solar zenith and satellite scan angles were added to the GVI dataset, forming the second generation GVI product. This additional information made the GVI a unique tool for global land studies although a number of challenging remote sensing and data management issues still needed to be properly addressed.

In 1989, analysis and re-processing of the GVI dataset became a core project of the NOAA Climate and Global Change Program. The goal of the GVI project was to analyze and improve the GVI dataset to make it more useful for climate change related applications, and the present paper summarizes its accomplishments. A generic processing scheme for AVHRR data over land was worked out. Uniformity of GVI data in time was improved by applying an updated AVHRR calibration and by reducing noise with better cloud-screening. The following climate-related GVI products are presently available: monthly 0.15° global maps of the top-of-the-atmosphere reflectances, NDVI, brightness temperatures, a precipitable water index, and associated 5-year climatologies (means and standard deviations). These variables and their monthly standardized anomalies are available starting April 1985. All these data products show potential for investigation of large scale land surface variability, and for detecting environmental events, such as droughts and floods, that strongly affect vegetation development. The monitoring of moderate year-to-year surface variability requires further suppression of noise, enhancement of the signal and removal of residual trends in data.

The experience, gained from work with the GVI data, is instrumental in creating and processing new generation 8-km Pathfinder (Ohring and Dodge 1992; James and Kalluri 1994) and 1-km IGBP (IGBP 1992) AVHRR datasets. Until these new and superior datasets replace it in the future, the GVI retains importance for both remote sensing and environmental scientists because of easy access to the original AVHRR radiances in four channels with associated viewing-illumination geometry and the new data products described herein.

The information content of AVHRR measurements over land is discussed in Section 2. An overview of the basic steps in data processing is given in Section 3. Section 4 concerns different aspects of land monitoring. Section 5 describes the present status of the GVI data products, including a prototype system for global operational land monitoring, and discusses remaining uncertainties and potential enhancements. Conclusions are given in Section 6.

2. INFORMATION CONTENT OF AVHRR MEASUREMENTS OVER LAND

The AVHRR is flown on board the NOAA polar-orbiting satellites, the first of which was launched in 1978. These satellites are nearly sun-synchronous flying at the altitude of about 850 km. With each pass, data are collected in a cross-track scanning mode along a swath about 2700 km wide, covering a range of viewing angles up to 56°. Each 24 hours, global coverage consisting of 14.1 orbits is achieved, with one look during the daytime and one during the night. Under normal conditions, NOAA operates two polar-orbiters, one in the morning and one in the afternoon. The second generation GVI contains data only from daytime orbits of the afternoon satellites NOAA-9 (April 1985-November 1988) and NOAA-11 (November 1988-September 1994). These satellites cross the equator between 1400 and 1700 local solar time, with the equator crossing time drifting to a later hour as the satellite ages (Price 1991). Satellite orbit drift results in a systematic change of illumination conditions and local time of observation -- one of the main sources of nonuniformity in multiannual satellite time series.

The AVHRR has 5 channels in the visible, near-infrared and thermal infrared (IR) regions of spectrum: channels 1 (0.58-0.68 μm), 2 (0.73-1.0 μm), 3 (3.6-3.9 μm), 4 (10.3-11.3 μm), and 5 (11.5-12.5 μm). All these channels have been chosen within the relatively transparent atmospheric windows to allow observations of the surface. The first two channels measure solar reflected light, whereas the land-atmosphere Planck emittance dominates in the thermal IR channels 4 and 5. Channel 3 is the most complicated case since both emitted and reflected solar components are comparable in this waveband. That was one of the reasons, in addition to frequent noisiness, for excluding channel 3 from the GVI dataset, and, therefore, analysis of its information content is not given here. A brief review below discusses the information content of AVHRR measurements over land in cloud free conditions. In studying the land surface, clouds should be excluded from the data since they obscure the signal from the surface in AVHRR wavebands.

2.1 Solar channels (channels 1 and 2)

Surface reflectance. The surface reflectance is characterized by the bidirectional reflectance distribution function (BRDF) -- reflectance as a function of the observation-illumination geometry (e.g. Pinty and Verstraete 1992; Roujean et al. 1992; Cihlar et al. 1994). BRDF depends on the type of soil/vegetation and surface topography. If the BRDF is known, one can integrate it hemispherically to estimate the hemispherical spectral surface albedo for a particular band, but the limited range of AVHRR viewing geometry complicates derivation of the hemispherical albedo. Semi-empirical relationships (e.g. Laszlo et al. 1988) can be used to convert spectral albedos into an integral over the full spectral domain -- the broadband albedo, needed as an input to some numerical climate models.

Vegetation Index. Availability of the 0.73-1.0 μm band makes AVHRR most attractive in studying processes at the biosphere-atmosphere interface. In this channel, the surface reflectance sharply increases for green vegetated surfaces as compared to soil/senescent vegetation. In channel 1, the presence of chlorophyll in green vegetation reduces the observed radiances (see e.g. Curran 1980).

Combining the AVHRR solar channels, Ch1 and Ch2, allows one to enhance the contrast between green vegetation and soil/senescent vegetation. The most widely used combination is the Normalized Difference Vegetation Index, calculated as NDVI=(Ch2-Ch1)/(Ch2+Ch1). This particular combination was first proposed by Rouse et al. (1973) (not specifically for AVHRR) and has proved to be very useful because it partially compensates for changing illumination conditions, surface slope and viewing aspect -- factors that strongly affect observed radiances. The NDVI as a preferred index for monitoring vegetation was reenforced by an analysis of different spectral indices (Tucker 1979). Since the early 1980s, top-of-the-atmosphere NDVI derived from AVHRR has been extensively utilized for mapping vegetation on the continental and global scales (e.g. Tarpley et al. 1984; Tucker et al. 1985).

There is, however, an ambiguity in what NDVI measures, which stems from the unresolved combination of the amount and state of the vegetation in the radiometer field of view (Curran 1980). Usually, these two quantities are correlated since development of vegetation is associated with the increase of both chlorophyll amount and area coverage by the vegetation. The NDVI signal, however, saturates before other measures of vegetation amount, such as Leaf Area Index (LAI) (e.g. Carlson et al. 1990). In any event, because of strong seasonal and spatial signals, this "simple" index of vegetation has been extensively utilized by the research community for more than a decade. In addition to analyzing vegetation distribution, monitoring its seasonal and interannual variability, relating it to ecological variables and (e.g. Malingreau 1986; Cihlar et al. 1991), it has also been suggested that NDVI be used in numerical models (see review by Gutman (1990)) for estimating the ratio of actual to potential evapotranspiration (Mintz and Walker 1990), the ratio of soil heat flux to net radiation (Kustas et al. 1994), canopy resistance and photosynthesis (Sellers 1985), and green vegetation fraction and LAI (Carlson et al. 1990; Price 1990), i.e. geophysical parameters identified by GEWEX as important for studying the land surface energy and water budget.

Atmospheric effect. The reflectances in AVHRR channels 1 and 2, ρ_1 and ρ_2, are affected by scattering/absorption processes in the atmosphere. The scattering is by molecules and aerosols (that may also absorb). Gaseous absorption in channel 1 is due to ozone, and in channel 2 to water vapor. Atmospheric effects are coupled in a complicated manner with surface BRDF. Thus, derivation of the surface albedo and surface vegetation index from satellite measurements require atmospheric corrections, discussed in detail by Tanré et al. (1992) and Arino et al. (1992).

2.2 Thermal IR (channels 4 and 5)

The brightness temperatures in AVHRR channels 4 and 5, T_4 and T_5 (K), depend mainly upon the surface temperature, total column atmospheric water vapor, and surface-atmosphere temperature gradient, so that the former two parameters can be estimated using split-window techniques (see e.g. Dalu 1986; Kerr et al. 1992; Prata 1993).

Land Surface Temperature (LST) is a useful piece of information for surface characterization. However, there is some ambiguity in its definition because of the complex character of the land surface -- its heterogeneity, roughness, and multilevel vegetation (e.g. Li and Becker 1993). The split-window technique for LST retrieval usually is based on a linear combination of T_4 and T_5. The accuracy of the estimated LST is restricted mainly by the effect of unknown and spectrally variable emissivity, which is a function of soil/vegetation type, topography, and observation geometry (Prata 1993).

Precipitable Water Index (PWI). Dalu's (1986) theoretical considerations show that under certain assumptions total column atmospheric water vapor amount (total precipitable water) can be derived over the ocean in clear conditions using the difference between the two AVHRR brightness temperatures. A precipitable water index can thus be introduced as $PWI=T_4-T_5$. Recent investigations analyze the potential and limitations of using PWI to estimate water vapor amount over land (Justice et al. 1991; Eck and Holben 1994). Variable aerosols, surface emissivity and surface-atmosphere temperature gradients, are the major factors affecting the relationship between PWI and the actual water vapor amount.

2.3 Combining solar and thermal IR channels

A combination of NDVI and LST was proposed as a method for assessing the surface moisture status and fractional vegetation cover over non-uniform land surface (Carlson et al. 1990; Price 1990; Nemani et al. 1993). The basic physical assumption is that the more heavily vegetated surfaces are associated with greater evapotranspiration and hence should be cooler than the less vegetated ones. Another reason that soil temperatures are higher than canopy foliage temperatures is the greater efficiency of the leaves at shedding absorbed energy (Choudhury 1989). Friedl and Davis (1994) indicate that in "well-watered" conditions the proportion of the soil background in the radiometer field-of-view, rather than evapotranspiration, explains the observed NDVI-LST negative correlation.

3. GENERIC PROCESSING OF AVHRR DATA

This section and Section 4 are pertinent to AVHRR data use in general, and the GVI dataset, in particular. The present section proposes an "ideal" processing scheme, which indicates the data flow and production, based on our experience with the GVI project. It should not be confused with the present accomplishments of the GVI project described in Section 5. Although the introduction of a new structure in this review paper may appear as a complication, the lack of consensus on processing and nomenclature motivated us to present our views on these important issues here. The structure, given below, facilitates general overviewing of the main levels in data production and evaluating the present status of the GVI data products, as well as those within other projects.

Data for climate studies are usually subdivided into three general levels: A) primary instrument readings; B) retrieved geophysical parameters after appropriate quality assurance; C) fields prepared from level B data. Our experience with GVI data suggests that one more, D-level, should be added to distinguish between generating complete fields and their statistical analysis. The presently proposed structure complies with the above categorization as well as with the data nomenclature in the International Satellite Cloud Climatology Project (Rossow and Schiffer 1991).

The A-level involves pre-processing of the acquired satellite sensor readings. This level is described in detail by NOAA's documentation, such as NOAA Polar Orbiter Data Users Guide (Kidwell 1991), and therefore is not addressed here.

The B-level includes calibration and radiometric corrections of the A-level data, identification of the pixels that can be used for land studies, and transformation of the bi-directional reflectances, ρ_1 and ρ_2, and brightness temperatures, T_4 and T_5, into climate-related land variables (surface albedo and temperature, fraction of vegetation, LAI, photosynthetically active radiation, etc.). The B-level data are mostly remote-sensing oriented. They include auxiliary information, such as observation-illumination geometry, calibration coefficients, Quality/Cloud (QC) flags, that allow tests and development of methods to improve the quality of data products.

Steps in the B-level processing are shown in Fig.1. The AVHRR data are supplied with information on navigation and pre-launch calibration appended but not applied, and are usually referred to as the NOAA 1B-level -- B1 in our notation. The data mapped daily into a regular geographical grid are denoted as B2. Temporal sampling is usually done by compositing procedures. The composite maps are referred to as B3. This stage provides users with BX.0 data (X=1,2,3): B1.0 (orbits), B2.0 (daily maps), B3.0 (composite maps). Any of them may be used as a starting point for further processing. BX.0 data contain original raw counts in AVHRR channels and information on calibration, navigation and observation-illumination geometry.

The first step of B-level data processing involves calibration -- conversion of sensor counts to physical quantities -- ρ_1, ρ_2, T_4, T_5 -- leading to BX.1 data products. At the next step, BX.2, quality/cloud identification of each pixel is done, with the results of different tests being packed in QC flags. The generated QC maps are appended to BX.1, making it the BX.2 data. Corrections for atmosphere, and surface anisotropic and diurnal variabilities are made at the next two steps, BX.3 and BX.4, respectively. Transformation to land surface parameters is carried out at the final step BX.5. The last three steps are made by means of look-up tables so that the whole image, independent of QC flags, is transformed with efficient use of computer time. The decision which pixels are retained for land studies is made at the next level. Note that most of the boxes have two arrows coming in and two coming out, which implies that the processing sequence is non-unique and that the derived product (at each step) can be obtained in more than one way. The path that is used to derive the product thus should be added in a more detailed version of the proposed nomenclature.

To identify the time/space resolution of data products, we propose a flexible nomenclature: BX.Y/TS, where X=1,2,3 and Y=1,2,3,4,5 denote the stage and step of the B-level at which the product was generated and TS stands for the temporal and spatial resolutions, respectively. For example, T can be H, D, W, Dk, M, S, or Y for hourly, daily, weekly, dekadal, monthly, seasonal and yearly, respectively. It is implied that at the B-level the original dataset resolution is not degraded, e.g. S=1, 8, 15 standing for 1km, 4km, 8 km, 15 km, respectively.

The C-level data are for the users who need products for, e.g., initialization and validation of models and do not want to spend time and resources on processing the remotely sensed data. At this level (Fig.2), the B-data are used as input, all auxiliary information is omitted, the QC flags are applied and complete fields of the variables are produced by spatial/temporal averaging-interpolation-smoothing. The areas with missing data resulting from QC flags application are filled in by interpolation. Averaging/smoothing is done to filter out some residual noise due to imperfections in the original data (e.g. sampling) and the B-level processing. Some of the signal (e.g. surface spatial variability) may be lost as a result of smoothing so that the effective product resolution becomes lower. Using the TS mnemonics described above, the C-level data products can also be presented as CX.Y/TS with temporal/spatial scales specified. The latter could be already different (i.e. with degraded resolution) from the B-level data products that were used to generate the C-products.

The D-level involves statistical analysis of the C-level data. The D-products may include climatology in terms of multiannual means and standard deviations with the original or reduced spatial resolution, relationships between various parameters on different spatial/temporal scales, and other statistics. The D-level products are most useful for climate analysis. Combining the D- and C-level products can be utilized for monitoring purposes, as described below. The nomenclature introduced above is applicable to the D-products as well.

4. LAND MONITORING ASPECTS

This section discusses the issues related to monitoring from AVHRR, in general. Only some, but not all, of these aspects have been accounted for in the GVI data products at present. Some are still in a research and development stage. The present status of the GVI data production and the issues to be resolved are described in the next section.

Standardized anomalies. We define monitoring as detection of anomalies $\Delta=V-\langle V\rangle$, i.e. deviations of the observed quantities, V, from their multiannual means $\langle V\rangle$. In order to quantitatively estimate the extent (reality and magnitude) of the anomalies, one has to have a reference noise level, with which the anomalies should be compared (Malingreau 1986) and which is provided by the climatological variance around the mean, σ^2. Assessment of statistical significance of the anomalies as compared to the level of inherent local year-to-year fluctuations is done by considering standardized anomalies $\delta=\Delta/\sigma$. The above approach is hardly new and has been used in climate studies for decades. The lack of long-term satellite datasets has prevented this method from being widely utilized in remote sensing.

Multi-parameter monitoring. AVHRR has 5 spectral bands, allowing retrieval of many land surface geophysical parameters. Although a comprehensive monitoring system should use all of them, usually, only one monitoring parameter is used, e.g. NDVI, which fails to characterize the surface fully. In aggregating NDVI, individual information from solar channels is lost. Furthermore, the thermal IR channels provide additional information. For example, both droughts and floods are associated with lowered NDVI, but have different IR signatures. Using several monitoring parameters derived from AVHRR reduces the ambiguity in interpretation of statistically significant anomalies.

Using Top-Of-Atmosphere (TOA) parameters. Monitoring of land surface implies the use of surface geophysical parameters, such as LAI or fraction of vegetation (i.e. CX.5 data in our nomenclature). However, retrieval algorithms for surface parameters are not always available or reliable. An equivalent approach to monitoring can be based on the standardized anomalies of surface ρ_1, ρ_2, NDVI, T_4, and T_5 normalized to a common observation-illumination geometry and time of day ($\delta_{CX.4}$). If the latter effects contribute negligibly to the variance of remote signal, then $\delta_{CX.3}$ may be used. If most year-to-year variability in the observed data comes from the surface (since atmospheric window regions are used, and surface contribution is expected to dominate), even standardized anomalies of TOA parameters ($\delta_{CX.2}$) can be utilized for most practical purposes. Screening of cloud contamination is, however, mandatory. The presently developed monitoring system within the GVI project, based on calibrated and cloud-screened TOA composite data (C3.2), is described in Section 5.4.

Limiting factors. The use of AVHRR for monitoring is seriously hampered because of nonuniformity of the satellite time series. This includes satellite/sensor discontinuities due to satellite/sensor change, and trends caused by sensor instability (Kaufman and Holben 1993) and by satellite orbit drift (Price 1991). The AVHRR solar channels are not calibrated in flight and degrade with time, which is taken care of by applying post-launch calibration (Rao and Chen 1994). The satellite-to-satellite change and orbital drift affect all variables because of changing illumination and diurnal surface/atmosphere variability. Large scale atmospheric perturbations from volcanic eruptions like Mt. Pinatubo contribute to nonuniformity of time series because stratospheric aerosols produced by these eruptions have a strong and persistent impact on observed radiances, mostly in solar channels (Stowe et al. 1992). All the above factors present difficulties in using AVHRR data if atmospheric/angular corrections are not applied at the B-level.

5. THE PRESENT STATUS OF GVI DATA PRODUCTS

The GVI products that have been routinely available at NOAA are B2.0 (daily maps) and B3.0 (weekly composite maps). The work in the GVI project has been based on weekly composites (B3.0). The creation of the third generation GVI consists of reprocessing the second generation GVI dataset (April 1985 - present) by the procedures described below and summarized in Fig. 3. Atmospheric, anisotropic and diurnal variability corrections and derivation of surface geophysical characteristics (dashed box) are bypassed in the current work but remain the subject of further research and development. The data products that have recently become available in addition to B3.0 are: B3.1/W15, B3.2/W15, C3.2/M15, and D3.2/M15.

5.1 GVI weekly products (B3.1/W15 and B3.2/W15)

The counts in AVHRR thermal channels are converted to T_4 and T_5 (Kidwell 1991; Kidwell 1994) and corrected for calibration non-linearity (Rao 1993). Reflectances in the solar channels, ρ_1 and

ρ_2, are calculated using the updated (Pathfinder) calibration (Rao and Chen 1994), which accounts for sensor degradation, and then corrected for Sun-Earth distance. The NDVI=$(\rho_2-\rho_1)/(\rho_2+\rho_1)$ and PWI=(T_4-T_5) are calculated at the B3.1 level to retain accuracy, since all B3 product values are packed into 8 bits.

Composite imagery in many parts of the world is often cloud contaminated, and should be cloud screened before any geophysical analysis. The B3.2 cloud/clear identification technique uses T_4-thresholds dependent upon month, region, and viewing angle as described in detail by Gutman et al. (1994). Together with updated calibration, the generation of QC flags is the major enhancement to the second generation GVI dataset. The B3.2 data products for the period April 1985 - present include weekly composite maps of the TOA ρ_1, ρ_2, NDVI, T_4, T_5, PWI, the associated solar zenith and satellite scan angles, and QC flags. The relative azimuth angle, i.e. the difference between solar and satellite azimuth angles, needed for atmospheric/ angular corrections, is not supplied with the dataset as a separate file, but is calculated within the reading program appended to the dataset. An example of a B3.2/W15 product -- weekly composite NDVI map with a QC mask -- is given in Gutman et al. (1994).

5.2 GVI monthly products (C3.2/M15)

The C3.2/M15 production flow includes the following steps: 1) QC flags are applied on a weekly basis, resulting in data gaps, 2) each quantity is averaged over one month for each map cell to partially fill in the data gaps and reduce some of the angular variability (the number of cloud-free weeks is stored as an additional map); 3) bi-linear spatial interpolation is applied to the missing data areas with persistent cloudiness in monthly averaged images; 4) 3x3 map cell smoothing is done to partially account for the imperfection of cloud screening, to filter out atmospheric and angular variabilities, and to compensate for random spatial sampling from GAC data into the GVI map cells. The above procedure yields monthly mean values for TOA ρ_1, ρ_2, NDVI, T_4, T_5, and PWI at each GVI map cell for each month of each year. Fig. 4 shows examples of C3.2/M15 products -- global monthly maps of T_4 for October 1993, January 1994 and April 1994. The T_4 map represents near maximum rather than daily mean brightness temperature, because of spacecraft mid-afternoon observation time.

5.3 GVI monthly climatology (D3.2/M15)

A 5-year climatology of means and variances at 0.15°-resolution (D3.2/M15) has been developed from the C3.2/M15 monthly fields of TOA ρ_1, ρ_2, NDVI, T_4, T_5, and PWI using data from April 1985 to December 1987 (NOAA-9), and from January 1989 to March 1991 (NOAA-11). The NOAA-9 data for 1988 and most of 1991 onward (after the Mt. Pinatubo eruption) were excluded since no angular/atmospheric corrections were applied.

Global maps of multiannual means and standard deviations of clear-sky AVHRR-derived variables have been generated for the first time under the GVI project, although global 3-year NDVI statistics have been available during the past year (Hastings and Di 1994). Fig. 5 shows the NDVI 5-year climatology for July. Despite the short 5-year base period, the areas with high interannual vegetation variability are clearly depicted on the map of standard deviations and are of particular interest to climatologists. The areas in central Siberia, southeast Australia, and northeast Brazil show high interannual NDVI variability, the latter being attributed to droughts caused by ENSO during the 5 years. Fig. 6 shows the completion of the annual cycle of the mean NDVI from Fig. 5. The areas in white (T_4< 270 K) are classified as stable snow/ice and in grey (270 K <T_4< 280 K) as transitional (unstable) snow/ice, both having ρ_1 > 20 %.

Fig. 7 shows the July climatology of ρ_1, T_4, and PWI. The global and seasonal distribution of PWI agrees with the observed distribution of precipitable water (Tuller 1968). This suggests a potential for PWI as a measure of large-scale water vapor distribution over land (see Section 2.2). The multispectral GVI data can be used for deriving other land variables, e.g. LST and albedo, and for improving classifications of bio-climates based on temporal analysis of NDVI alone (e.g. Tucker et al. 1985; Townshend et al. 1987).

5.4 Prototype of a global land monitoring system

A prototype global land monitoring system has been developed based on SGI UNIX workstations. It is an evolving system, in which some parts can be improved and/or replaced, and is suitable for routine operations, requiring very little human intervention.

Each week, composite B3.0 data are automatically accessed and copied to a UNIX workstation magnetic disc. The production of B3.1 and B3.2 follows, i.e. calibration and generation of QC masks. The enhanced weekly product is then appended to the existing NOAA archive. At the beginning of each month, the previous five B3.2 weekly products are processed at the C-level, i.e. the QC flags are applied and monthly averaging, interpolation and smoothing are carried out. Then, the monthly standardized anomalies are generated and made available for climate analysis and interpretation. Display of the seasonal and year-to-year dynamics on a global scale of the derived land products is now possible by means of the animation loops on the SGI workstation using a menu driven program and the Interactive Data Language (IDL) software.

An example of the standardized anomalies δ_{NDVI} for July over the U.S. during 1985-1994 (Fig. 8) illustrates the multiannual potential of the GVI products. (Note that the positive and negative anomalies for the whole time series are not mutually balanced since the base period for climatology development includes only five of the nine presented years.) In general, the derived anomalies compare well with the maps of the Palmer Drought Index produced by NOAA and the United States Department of Agriculture, except for some special situations. For example, the areas, where the 5-year mean NDVI estimates are biased, are not easily interpreted, particularly in the west, where PDI indicates dry conditions during all five years. Additionally, the desert areas in the west show a "greening" trend during 1991-1993, which may be attributed to residual calibration error for NOAA-11 (this effect is counterbalanced by the impact of solar zenith angle in 1994) (Gutman and Ignatov 1995). Furthermore, both moisture deficit (droughts) and excess (floods) are associated with lowered NDVI. The "Great Flood" of 1993 in the area of Iowa and the flooding of 1994 in northern Florida appear as patterns of negative anomalies in Fig. 8. Additional information, such as thermal IR and/or microwave measurements, evidently should be used to distinguish insufficient from excessive moisture conditions. The derived temperature anomalies δ_{T4} are affected by the diurnal variability of the observed brightness temperature as a result of satellite orbit drift (see Section 4), which presents difficulties in monitoring AVHRR temperatures (Gutman and Ignatov 1995). Corrected temperature time series from AVHRR and/or data from other sensors should alleviate this problem.

5.5 Remaining uncertainties and potential enhancements

All of the levels of processing have potential for improvement. The calibration and cloud screening can be refined. The B3.3-B3.5 products are yet to be generated. The use of optimal averaging and interpolation on the C-level is preferable to fill in the data gaps. These, however, require the spatial/temporal correlation functions, which are not available now. The D-level can be improved by using longer time series and developing other statistics. *Atmospheric, anisotropic and diurnal variability effects.* The major distortion of the signal in solar channels by the atmosphere is due to aerosol and water vapor. Global observations of these constituents are not readily available. Research is underway to derive this information from AVHRR data, e.g. using PWI for water vapor amount (Eck and Holben 1994). Much effort has yet to be invested to correct data for stratospheric and tropospheric aerosol effects. Several studies have shown that much of the contribution to angular variability in the observed radiances is due to surface anisotropy (Roujean et al. 1992). Thus, even if the atmospheric corrections are made, it is unclear how the results could be interpreted. A single globally applicable correction is not possible due to variability of surface effects in space and time. Models of only a few vegetation types are unlikely to be generic because of topograhy and mixture of vegetation types. Surface and atmospheric diurnal variability is most pronounced in the thermal data, resulting from satellite orbit drift. Normalization to common observation time is needed for monitoring interannual variability in surface temperature.

An alternative approach. Since atmospheric, anisotropic, and diurnal variability corrections of GVI data are presently infeasible, an alternative approach has been proposed for developing TOA regional empirical angular/diurnal variability functions (REAF) for each limited region of the global land surface for limited periods, e.g. monthly (Gutman 1994a,b). (Note that diurnal variability can be expressed as sun angle dependence for a given latitude; geostationary satellite data could be used for developing this dependence.) The number of the REAFs may be reduced using cluster analysis at a later stage. The REAFs are in turn utilized to normalize all data to a common sun-target-sensor geometry. Pilot studies indicate that the time series become more stable after TOA normalization (Gutman 1994b; Ba et al. 1995). The effective elimination of angular biases allows more reliable interpretation of the results and widens the area of applicability for analysis. The methodology has to be improved and tested further before its global development is undertaken.

Lessons we have learned. While analyzing the operational production of GVI (B3.0), a number of lessons about data collection have been learned. These lessons indicate how the AVHRR data management could be improved and have implications for the NOAA/NASA Pathfinder AVHRR Land dataset. In the NOAA GVI operations, only afternoon satellite passes are collected, preventing diurnal variability studies on one hand, and leading to persistent cloud contamination in some areas, on the other hand. Data should be collected from each of the currently operating NOAA polar orbiters, allowing more coverage and opening new opportunities for research. Methods, other than compositing, should be developed to reduce data volume, preferably <u>after</u> cloud screening has been done. Cloud/clear discrimination should be done on the original daily images so that only clear pixels are mapped. Compositing, if unavoidable, should be done using NDVI. Compositing in the NOAA GVI collection is currently done by using maximum of a simple difference Ch2-Ch1, leading to a bias in observation geometry (Gutman 1991). Maximum NDVI compositing, however, is not appropriate in collecting clear observations over snow and desert regions. Additionally, the compositing procedures retain mostly cloud contaminated data over water surfaces. Since negative values of NDVI (and Ch2-Ch1) are observed over cloud free water, compositing by the absolute value would add information over water bodies in the composite imagery. A 10-bit precision is recommended for thermal IR channels, which are currently truncated to 8-bit precision, i.e. 0.5° K, in the NOAA GVI. All channels should be collected. Channel 3 in the GVI dataset collection could facilitate discrimination of snow from clouds and detection of aerosols. Most of these recommendations are already in effect in the Pathfinder processing scheme and should be implemented in NOAA's operations.

6. CONCLUSIONS

An overview of research and development with the NOAA Global Vegetation Index dataset under a core project of the NOAA Climate and Global Change Program has been given, and the enhanced GVI data products described. All the products (B3.2/W15, C3.2/M15, and D3.2/M15) are available from NOAA archives. The D3.2/M15 will also be available on CD/ROM. The C3.2/M15 and D3.2/M15 products reside on a UNIX system at National Environmental Satellite Data and Information Service (NESDIS) and will be made available for browsing and animation. The latter can be used for educational purposes to illustrate the global annual dynamics of vegetation cover, albedo, temperature, and water vapor.

The newly derived C- and D-products can be easily accessed by climatologists for the analysis of inter- and intra-annual land climate variability, such as response of the surface state to ENSO episodes. Deeper involvement of climatologists in the data products analysis and their close interaction with the "data producers" is imperative at this stage. Given the improvement of the data quality, the present study suggests that there is more potential in this dataset than previously thought (e.g. Thomas and Henderson-Sellers 1987), although it should be born in mind that the remaining uncertainties limit this potential. The annual global distribution of the GVI variables is presently more reliable than the derived interannual variability, which is useful only when the surface change is relatively strong compared to the noise level. Further reduction of noise and removal of trends will increase the monitoring potential of AVHRR land data.

The operational production of monthly anomalies continues. The previous month's anomalies are available during the second week of the current month. Weekly monitoring for the areas with frequent cloud free skies can be developed if more progress is achieved in angular/atmospheric corrections.

Despite the remaining uncertainties in the monthly GVI data products, their information content is higher than that of the GIMMS-derived 1°x1° NDVI monthly dataset (Los et al. 1994) because of finer spatial resolution, the availability of individual channel reflectances and temperatures, and more accurate cloud screening. The GVI dataset is unique in that it is global, multiseasonal, multispectral, and multiannual. These GVI features are useful not only for environmental studies and numerical modeling, but also for further development of the remote sensing methodology and processing of the 8-km Pathfinder and 1-km IGBP AVHRR datasets. Both Pathfinder and the 1-km projects can utilize the GVI experience for generating C- and D-level products for environmental research community. Development of the GVI data products contributes to the activities within IGBP, GEWEX, and, particularly, ISLSCP.

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Table of frequently used acronyms and notations

AVHRR	Advanced Very High Resolution Radiometer
BRDF	Bi-directional Reflectance Distribution Function
GAC	Global Area Coverage
GEWEX	Global Energy and Water Cycle Experiment
GIMMS	Global Inventory Monitoring and Modeling Studies (at NASA)
GVI	Global Vegetation Index (dataset)
Ch1, Ch2	Channels 1 and 2 of AVHRR
δ_V	standardized anomaly of variable V
IGBP	International Geosphere-Biosphere Programme
ISLSCP	International Land Surface Satellite Climatology Project
IR	Infrared
LST	Land surface temperature
LAI	Leaf area index
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmosphere Administration
NDVI	Normalized Difference Vegetation Index
NESDIS	National Environmental Satellite Data and Information Service
PWI	Precipitable water index
QC	Quality/cloud flag
REAF	Regional Empirical Angular Function

ρ_1, ρ_2	Channel 1 (visible) and 2 (near-IR) bidirectional reflectances
T_4, T_5	Channel 4 and 5 brightness temperatures
TOA	Top-Of-Atmosphere
X.Y/TS	X=1,2,3 (1-orbits, 2-daily maps, 3-composite maps)
	Y=1,2,3,4,5 (1-calibrated, 2-QC flag appended,
	3-atmospherically corrected, 4-surface BRDF-corrected
	5-transformed into geophysical parameter
	TS mnemonics: T-time scale, S-spatial scale

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Figure captions

Fig. 1. The B-level of the generic AVHRR processing scheme

Fig. 2. The C-level of the generic AVHRR processing scheme

Fig. 3. A schematic summary of the procedures used for GVI data products.

Fig. 4. Global monthly mean maps of T_4: October 1993, January 1994 and April 1994.

Fig. 5. Global NDVI 5-year July climatology: means (top) and standard deviations (bottom). Fig. 6. Global NDVI climatology (means) for October, January and April. The areas in white (T_4 < 270 K) are classified as stable snow/ice and in light grey (270 K < T_4 < 280 K) are classified as transitional (unstable) snow/ice, both having ρ_1 > 20 %.

Fig. 7. Global 5-year July climatology (means) of the ρ_1, T_4, and PWI.

Fig. 8. Standardized anomalies of NDVI for the U.S. in July (1985-1994), defined as departures from the 5-year means divided by the 5-year standard deviations.

FOR THE COVER:

Vegetation condition for July (1985-1994) over the conterminous United States as manifested by standardized anomalies (departures from the 5-year means divided by the 5-year standard deviations) of the normalized difference vegetation index (NDVI). Positive anomalies of NDVI (good vegetation conditions) are shown in green and negative anomalies (poor vegetation conditions) in yeallow/orange. They have been developed using the enhanced NOAA global land dataset from the Advanced Very High Resolution Radiometer (AVHRR). See article by G. Gutman et al., page XX.