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Considerations of and Improvements to Large-Scale Vegetation Monitoring

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Abstract—The NOAA-7 polar orbiting sun-synchronous operational satellite carries the 5-channel advanced very high-resolution radiometer which acquires data globally at a spatial resolution of 4 km on a daily basis. These data provide a means for frequently monitoring global vegetation at continental scales. Techniques for compositing and cloud screening a green leaf density vegetation index product for Africa are presented for 9 sequential days beginning August 16, 1982 and are compared with a semi-operational vegetation index product produced by NOAA.

INTRODUCTION

THE ADVANCED very high-resolution radiometer (AVHRR) carried on the present NOAA series (NOAA-6, NOAA-7, etc.) of polar orbiting operational meteorological satellites has been shown to be capable of monitoring vegetation dynamics in the Nile River Valley and Nile Delta of Egypt [1] and the Senegalese Sahel [2] for studying vegetation-climate gradients [3] and for identifying large-scale deforestation in the Amazon Basin [4]. These regional studies used 1-km or local area coverage (LAC) data from the AVHRR sensor. Continental and global scale studies, however, must use 4-km or global area coverage (GAC) data since satellite data storage limitations do not allow daily global coverage with 1-km data.

Both GAC and LAC data come from the same AVHRR

sensor. On-board data processing generates the GAC data stream by averaging and subsampling the AVHRR output. Nonmeteorological use of multispectral AVHRR data from the visible and near IR bands, 0.55–0.68 and 0.73–1.10 μm , respectively, began in 1980 after the launch of NOAA-6 and was first reported by Schneider *et al.* [5]. Early work concentrating on vegetation monitoring using NOAA-6 has also been reported [6]–[8]. Spectral bands usually recommended for green vegetation monitoring are 0.6–7.0 μm (chlorophyll absorption) and 0.75–0.9 μm (leaf reflectance). The AVHRR bands are broader and do include a major water vapor absorption region from 0.9–1.0 μm ; however, the two bands are split at 0.7 μm where the vegetation contrast is the strongest. It should be noted that the first AVHRR flown (NOAA-5) had the first visible channel set at 0.55–0.90 μm which made it unsuitable for vegetation monitoring. Future narrowing of channel 2 from 0.73–1.10 μm to 0.80–0.90 μm would further improve performance of channel 2 by avoiding the water vapor absorption band and narrowing channel 1 from 0.55–0.68 μm to 0.60–0.68 μm would improve performance of channel 1 by reducing shorter wavelength scattering.

SATELLITE AND DATA CHARACTERISTICS

NOAA-7 is a polar orbiting sun-synchronous operational satellite in the TIROS-N series. It operates with a local equator crossing time of 0230 h (descending) and 1430 h (ascending) at an altitude of 850 km and an orbital period of

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Fig. 1. Channel 1 and channel 2 radiance characteristics over the Nile Delta during summer 1981. (a) June 6, (b) June 28, (c) August 11.

102 min. AVHRR and other sensor data are recorded on spacecraft tape recorders and are transmitted nearly every orbit to ground stations in Alaska or Virginia [9].

The AVHRR is a cross-track scanner operating at 360 r/min with an instantaneous field-of-view (IFOV) of 1.3 mrad and a swath width of approximately 2800 km. Data are digitized at 10 bits for all five channels and are acquired for scan angles of ± 56 degrees. At nadir the resolution is 1.1 km decreasing to 5.5 km at the scan limit. The wide swath scan provides contiguous global coverage at the equator on a daily basis. At higher latitudes considerable swath overlap occurs. During each scan 2048 samples are taken. Thus the sensor data rate from the AVHRR is $(360/60)(2048)(5)(10) = 614$ kbits/s. This is a moderate data rate and is transmitted continuously in real time via the high-resolution picture transmission (HRPT) service to local users equipped with appropriate ground stations. Two such stations provide U.S. coverage and various other stations exist around the world.

GAC data are obtained via on-board processing and recording where the basic sensor data is reduced by 1) averaging 4 contiguous samples along a scan line and skipping the fifth sample, and 2) storing data from each scan line in an on-board buffer with only every third scan read out. Thus the GAC sensor data rate from the AVHRR is $(360/60)(1/3)$

$(2048/5)(5)(10) = 40.95$ kbits/s. The sampling rate is approximately 1.36/IFOV with 4 samples covering 3.2 km at nadir in the cross track direction. Along the track of the subsatellite point, however, the resolution remains 1.1 km with a 2.2-km gap between samples. The gap cross track is 0.8 km. It should be noted that GAC data are normally referred to as "4-km data"; however, the data compression used is not a simple average but is an average of the partially sampled 3×5 pixel block. In partly cloudy regions this offers the statistical opportunity to acquire cloud-free data even when the cloud gaps are less than 4 km. GAC data for the 14.2 orbits acquired each day covering the entire earth's surface from 60 south to 85 north latitude represent a large but manageable volume of data. In 8-bit bytes it is $2 \times (40.9 \times 10^3)(60 \times 102)((60 + 85)/360)(14.2)/8 = 358$ Mbytes.

NORMALIZED DIFFERENCE VEGETATION INDEX CHARACTERISTICS

A differential vegetation signature is observed between the 0.55–0.68 μm and 0.73–1.1 μm bands when a vegetated region such as the Nile Delta is encountered (see Fig. 1) since chlorophyll absorption reduces the channel 1 signal and the green leaf density associated with the chlorophyll present

TABLE I

r	I_1	I_2	dI_2/dI_1
0.0	1.0	1.00	2.00
0.2	0.8	0.67	1.38
0.4	0.6	0.43	1.02
0.6	0.4	0.25	0.78
0.8	0.2	0.11	0.62
1.0	0.0	0.00	0.50
1.2	-0.2	-0.09	0.41
1.4	-0.4	-0.17	0.35

increases the channel 2 signal. The transects shown for the Nile Delta area of Egypt begin over water at 32 north, 32 east and end over desert at 30 north, 30 east for the dates June 6, June 28, and August 11, 1981. By August the signal from channel 1 has dropped nearly to the value for the sea and channel 2 has increased nearly to the value of the desert.

Consider an index based on the normalized difference of the channel 2 and channel 1 radiances; that is

$$I_1 = (L_2 - L_1)/L_2 = 1 - (L_1/L_2) = 1 - r. \quad (1)$$

Or the alternate form used in our studies

$$I_2 = (L_2 - L_1)/(L_2 + L_1) = (1 - r)/(1 + r). \quad (2)$$

Thus a normalized difference is just a transformation of the ratio index r where I_1 is linear and I_2 is nonlinear. The I_2 index can be written as a function of the I_1 index

$$I_2 = (1 - (1 - I_1))/(1 + (1 - I_1)) = I_1/(2 - I_1) \quad (3)$$

and its derivative expressed as

$$dI_2/dI_1 = 2/(2 - I_1)^2. \quad (4)$$

Thus the enhancement feature provided by the I_2 index is a lower sensitivity to ratio changes for small and negative I_1 values as shown in Table I. For this reason the index I_2 has been used as the preferred index in our vegetation monitor studies.

OFF NADIR THROUGH THE ATMOSPHERE VIEWING

Given the sensor view angle, the scene solar angles, and an atmosphere model, the relationship between radiance (L) at the top of the atmosphere and the surface reflectance ρ can be approximated by a linear equation

$$L_i = A_i + G_i \rho_i \quad (5)$$

where A_i is the backscattered atmospheric offset and G_i is the atmospheric attenuation combined with the solar spectral intensity. Thus the I_1 index can be written, with R now being the surface ratio ρ_1/ρ_2 , as

$$I_1(R) = (L_2 - L_1)/L_2 \quad (6)$$

or

$$I_1(R) = (G_2 \rho_2 - G_1 \rho_1 - (A_1 - A_2))/(G_2 \rho_2 + A_2). \quad (7)$$

Let

$$B = G_1/G_2. \quad (8)$$

Then

$$I_1(R) = (1 - BR - e_0)/(1 + e_1) \quad (9)$$

Fig. 2. Single day coverage for August 16, 1982, at 16-km resolution. Scale for vegetation is dark gray for bare soil to white for intense vegetation. Screened cloudy regions and no data regions are displayed black. Ocean areas are geographically masked and displayed as light gray.

with

$$e_0 = (A_1 - A_2)/G_2 \rho_2 \quad (10)$$

and

$$e_1 = A_2/G_2 \rho_2. \quad (11)$$

The gain ratio B is reasonably constant for changing surface types, solar illumination, and scan angles; thus e_0 and e_1 are the first-order error terms. As the AVHRR scans off nadir, the atmospheric slant path increases causing both A_1 and A_2 to increase. The term e_0 remains positive, A_1 being associated with the shorter wavelength channel. Holding R and ρ_2 constant, the effect of both e_0 and e_1 increasing is to reduce to value of the index as observed from the top of the atmosphere. In the next section the observational confirmation of this effect is discussed (see Fig. 4 later).

The effects of off nadir through the atmosphere viewing are seen more directly in the expression for the I_1 index. The corresponding change in the I_2 index can then be obtained using (3) and (4).

COMPOSITING INDIVIDUAL GAC DAYS

To cover the African continent three orbits each day were acquired from latitude 35 south to 38 north for 9 days beginning August 16, 1982. For each day the I_2 vegetation index was generated using a cloud screen based on the brightness temperature of the thermal infrared channel 5 (11.5–12.5 μm). Over Africa in August a screen threshold of 14°C (62.8°F) was used. This was determined by analysis of numerous clouds over Africa and by comparison with concurrently obtained Meteosat data. GAC data have 409 samples per scan line for a ± 56 -degree scan. In processing the daily product, 15 samples from both ends were deleted leaving the small gap between the orbital swaths obtained in Figs. 2 and 3.

No atmospheric offset correction was applied to the AVHRR data before the vegetation index was generated. This produces a significant variation in the index value as a

Fig. 3. Single day coverage for August 22, 1982 at 16-km resolution. Note change in location of square identifying sample area.

Fig. 5. First 3-day maximized composite at 16-km resolution. See Fig. 10 for vegetation index gray scale.

Fig. 4. Observed view angle effect on the normalized difference vegetation index. Black square in Figs. 2 and 3 identify the sample area.

Fig. 6. Second 3-day maximized composite at 16-km resolution.

constantly vegetated scene is sampled first on one edge of an orbital swath, then toward the center of the swath, and finally on the opposite edge. For the NOAA-7 satellite this travel takes approximately 9.2 days (the orbit mean repeat cycle).

To quantify the variation with viewing perspective using NOAA-7 data, we observed a highlands region in Southern Angola (see Figs. 2, 3, and 11) using the 9-day data set. This region was observed cloud-free for 8 of the 9 days from the analysis of concurrently obtained Meteosat data. Thus the I_2 index changes shown in Fig. 4 were caused by atmospheric/viewing geometry effects. There are 4 days when any region will be near the swath center where the variation is minimal (see also [10]). If one of these four are cloud-free, then the true maximum is retained in a 9-day composite; however, if only a day where the region is near a swath edge is cloud-free, then the maximum retained possesses a bias error relative to those regions observed cloud-free near the swath center.

As shown in Fig. 2, cloud cover over Africa was detected and identified by the 14°C thermal threshold, was quite

extensive, and was in agreement with the concurrently obtained Meteosat data. Fig. 5 shows a composite of the first three days, Fig. 6 the second three days, and Fig. 7 the last three days and note the reduction of cloudy regions (shown as black areas) which compositing produces. Figs. 8 and 9 present the 6- and 9-day composites, respectively. When nonzero values exist on more than one day in a sequence, the presently used compositing technique is to retain only the largest value. Also in the daily product shown in Fig. 2, which does not retain the full GAC resolution (only 640×512 total spatial elements), maximizing selection is also used when more than one AVHRR field-of-view location maps into a 16-km display pixel. A compositing technique where overlaying nonzero samples are averaged would require perfect cloud screening as well as an effective atmospheric viewing geometry correction.

On the 640×512 interactive display used for product generation and analysis, coverage of the African continent has been initiated using 3 sectors, each covering only 45 degrees of latitude, and has produced an 8-km product that more nearly matches the inherent GAC resolution. Fig. 10

Fig. 7. Last 3-day maximized composite at 16-km resolution.

Fig. 10. Single day coverage for August 22, 1982 at 8-km resolution.

Fig. 8. Six-day maximized composite at 16-km resolution.

Fig. 9. Nine-day maximized composite at 16-km resolution. See Fig. 10 for vegetation index gray scale. Remaining cloudy regions appear black.

Fig. 11. 10-day 8-km color scaled composite for July 1-10, 1983, of Southern and Northeast Africa. Continually cloudy regions appear white.

shows a single day's image produced for the Southern section. The display pixel size is constant and the footprint spread with increasing scan angle causes the pattern of data gaps near the swath edges. Fig. 11 shows a refined 8-km

product for Southern and Northeast Africa composited from July 1-10, 1983. In the vegetation index color scale brown represents the zero value returned by bare areas and vegetation intensity increases through the orange, yellow,

Fig. 12. Color coded display of NOAA's 7-day composite for northern and southern hemispheres. Index color scale same as in Fig. 11. Limit on index negative values, but no geographic ocean mask so ocean regions can appear black (no data) or brown (zero or negative values). Note the pattern due to the effect of the day/night terminator on the index value in the southern hemisphere during August.

green, red, pink, and purple colors as shown on the color bar. Here the interval is 10 days and the scan angle has been limited to ± 45 degrees (center two-thirds of the swath). Separate composites for the odd and even days were generated; each was interactively examined and any bad points zeroed; and then the two were combined. Also a 3×3 , two-dimensional running average was used for spatial smoothing. Note that over some desert surfaces the value of the normalized difference is similar to that of lightly vegetated regions. Use of solar zenith angle corrected channel 1 radiances with an appropriate threshold setting at a minimum desert value should reduce this ambiguity.

GLOBAL PRODUCT GENERATION

Since April 1982, weekly vegetation images [11] indicating aggregated green leaf density or "greenness" as measured by the I_2 index have been produced as an experimental product by NOAA/NESDIS to develop and evaluate techniques for global agricultural monitoring. The 7-day product

consists of northern and southern hemispherical maps using the standard National Weather Service polar-stereographic projection as displayed in Fig. 12. Resolution in this product ranges from 15 km at the equator to 30 km at the poles. Data from individual GAC orbits are randomly sampled daily and the "greenest" value selected every week for each grid cell so that a map element retains the maximum value of the vegetation index observed by a GAC field-of-view at that point over the 7-day interval. There is no thermal IR cloud screen, no atmospheric/viewing geometry correction, and no spatial averaging. The maximizing technique is used to minimize the cloud and off-nadir viewing effect since both tend to reduce the observed I_2 value [10]. This experimental product was implemented at NOAA/NESDIS by modifying existing operational software and under computer resource limitations; however, it has proven to be a useful data base since it allows evaluation of the I_2 index over all continental regions for complete annual cycles.

SUMMARY

Global scale studies of vegetation using a medium-resolution large-swath-width orbiting multispectral sensor have identified several improvements that could be incorporated into an operational global product:

- 1) A cloud screen threshold using an IR channel so that continually cloudy areas over the compositing interval can be identified and labeled.

- 2) A compositing interval based on the satellite cycle repeat period (9.2 days for NOAA-7) instead of a weekly interval. This insures that every region in the product has the same number of observation days near the swath center.

- 3) A mapping projection more optimized for continental observations. The present hemispherical mapping with 15–30 km grid resolution does not retain full GAC resolution and requires remapping for continental products covering equatorial regions.

- 4) Developing techniques for removing atmospheric/viewing geometry offsets would enable the compositing interval to be reduced and data averaging used for those regions and seasons where clouds are not persistent.

- 5) Use of the absolute value of channel 1 corrected radiances as a desert threshold detector to provide better discrimination between desert surface features and lightly vegetated regions.

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A Preliminary Report on the Assessment of Wetland Productive Capacity from a Remote-Sensing-Based Model—A NASA/NMFS Joint Research Project

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Abstract—The NASA and the NMFS have undertaken a joint research project to develop Landsat Thematic Mapper (TM) technology for the determination of the value of wetlands to estuarine fish and shellfish production. NASA has developed the remote-sensing-based model to predict wetland productive capacity, a measure of the organic carbon exported to the estuarine food chain. The productive capacity (PC) model uses satellite remotely sensed determinations of vegetation, as the source of carbon, and distance-to-water, shoreline density, and water body type as hydrographic factors influencing carbon export. Regression analyses of aircraft simulated TM (TMS) data showed a stronger relationship with percent vegetation cover than with biomass for estimating the source of organic

detritus. Land/water discrimination, fundamental to the measurement of the hydrographic variables, was accomplished more accurately with TMS than with Landsat Multispectral Scanner (MSS) data as compared to a photographic standard. The PC model generates detrital export measurements as input to an estuarine ecosystem model being developed by NMFS. Initial findings show that salinity patterns along with animal interactions affect the utilization of detritus by benthic organisms. The coupling of the two models establishes a technique for estimating the economic value of wetlands with respect to estuarine-dependent fish and shellfish production.

Keywords—wetlands, trophic value, detritus, estuarine ecosystem, remote sensing, biomass, Thematic Mapper.

INTRODUCTION

THE NASA AND the NMFS have undertaken a joint research project to develop Landsat Thematic Mapper (TM) technology for the determination of the value of wetlands to living marine resources. Such a determination is

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