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GEMI: a non-linear index to monitor global vegetation from satellites

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Abstract

Knowledge about the state, spatial distribution and temporal evolution of the vegetation cover is of great scientific and economic value. Satellite platforms provide a most convenient tool to observe the biosphere globally and repetitively, but the quantitative interpretation of the observations may be difficult. Reflectance measurements in the visible and near-infrared regions have been analyzed with simple but powerful indices designed to enhance the contrast between the vegetation and other surface types, however, these indices are rather sensitive to atmospheric effects. The 'correction' of satellite data for atmospheric effects is possible but requires large data sets on the composition of the atmosphere. Instead, we propose a new vegetation index which has been designed specifically to reduce the relative effects of these undesirable atmospheric perturbations, while maintaining the information about the vegetation cover.

Terrestrial vegetation, which constitutes the bulk of the continental biomass (Ajtay *et al.* 1979), affects the climate system over a wide range of space and time scales by modifying the surface energy balance, and by influencing the exchanges of water and carbon between the surface and the atmosphere. The identification of green plant material is of great interest since leaves and needles are the site of photosynthesis and the prime link between the biosphere and the atmosphere. Plants have a distinctive spectral signature, characterized by a low reflectance in the visible part of the solar spectrum, and a high reflectance in the near-infrared region (Gates 1980). Radiance or reflectance measurements can therefore be used to detect the presence of growing vegetation, if the position and width of the spectral bands of measuring instruments are selected in the red and near-infrared regions, to take advantage of this feature (Tucker 1979).

Two indices are commonly used to exploit the spectral signature of plant materials. These are known as the 'Simple Ratio', defined as

$$SR = \frac{\rho_2}{\rho_1} \tag{1}$$

and the 'Normalized Difference Vegetation Index':

$$NDVI = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} = \frac{SR - 1}{SR + 1} \tag{2}$$

where ρ_1 and ρ_2 are the measured reflectances in the visible and near-infrared spectral regions, respectively. Clearly, $0 \leq SR < \infty$ and

$-1 \leq$ NDVI ≤ 1, with highly vegetated surfaces characterized by typical values of SR ≈ 10 or NDVI ≈ 0.8, and with values of SR ≈ 1.25 and NDVI ≈ 0.1 for bare soil surfaces. These indices have been empirically correlated to such variables as biomass, vegetation cover, leaf area index, productivity, carbon in the standing biomass, etc (Tucker *et al.* 1981; Verstraete & Pinty 1991; Sellers 1985; Asrar *et al.* 1985; Tucker *et al.* 1986).

Satellite platforms provide the most powerful technique available today to monitor environmental conditions in the atmosphere or at the surface, on a global and repetitive basis, and with sufficient spatial, temporal and spectral resolution. The measurements acquired by the Advanced Very High Resolution Radiometer (AVHRR) on board the NOAA satellites are of particular interest for the global observation of the biosphere because of the spectral position of the first two channels (channel 1: 0.58–0.68 μm, channel 2: 0.78–0.9 μm) and the existence of long series of data (up to 10 years) at least at the low spatial resolution of about 4 km. (Sellers 1987; Tucker *et al.* 1985).

Radiative measurements r obtained from remote sensing, including those made on board satellites, are complex functions of the state and properties of the surface and the atmosphere. Formally, this can be expressed as

$$r = r[\mathbf{s}(\mathbf{x}, t, \lambda, \Theta), \mathbf{a}(\mathbf{x}, t, \lambda, \Theta)] \quad (3)$$

where $\mathbf{s}$ and $\mathbf{a}$ are the surface and atmospheric properties or parameters that affect the transmission of radiation, respectively. These properties are themselves varying in space ($\mathbf{x}$) and time (t), with the wavelength of the radiation (λ), and with the geometrical conditions of illumination and observation (Θ). Bold letters represent vectors or sets of quantities.

Images of the spatial distribution or graphs of the temporal evolution of the SR and NDVI indices exhibit significant structure, and much work has been devoted to the exploitation of these features in mapping and event detection applications (Goward *et al.* 1986; Townshend & Justice 1986; Malingreau *et al.* 1985; Malingreau *et al.* 1989). The quantitative interpretation of these indices, however, is rather difficult because they are quite sensitive, among other variables, to the state of the atmosphere and to the geometry of illumination and observation (Holben 1986; Holben & Fraser, 1984; Holben *et al.* 1986; Lee & Kaufman 1986).

Global monitoring applications, which attempt to characterize the planetary surface by analyzing the spatial or temporal structure of these indices, implicitly assume that, outside cloudy areas, the observed variability reflects changes in the surface properties, rather than changes in atmospheric conditions. Symbolically, for a specific vegetation index (VI)

$$\frac{\mathrm{dVI}}{\mathrm{d}\mathbf{x}} = \frac{\partial \mathrm{VI}}{\partial \mathbf{s}} \frac{\mathrm{d}\mathbf{s}}{\mathrm{d}\mathbf{x}} + \frac{\partial \mathrm{VI}}{\partial \mathbf{a}} \frac{\mathrm{d}\mathbf{a}}{\mathrm{d}\mathbf{x}}$$

$$\frac{\mathrm{dVI}}{\mathrm{d}t} = \frac{\partial \mathrm{VI}}{\partial \mathbf{s}} \frac{\mathrm{d}\mathbf{s}}{\mathrm{d}t} + \frac{\partial \mathrm{VI}}{\partial \mathbf{a}} \frac{\mathrm{d}\mathbf{a}}{\mathrm{d}t} \quad (4)$$

and it is assumed that the first terms on the right hand side of the equation account for most of the variability present in the left hand side.

AVHRR measurements in the optical range, however, are affected by atmospheric conditions, which determine the intrinsic reflectance of the atmosphere and affect the transmission of radiation over the double path Sun-surface-satellite. Rayleigh scattering and ozone absorption affect the amplitude of the reflectance measured in the visible part of the spectrum, but these effects can be taken into account because they depend on parameters which vary little or predictably in space and time (mass of the atmospheric column and total ozone concentration). Aerosols scatter radiation, preferentially in the forward direction, and much more so at shorter visible wavelengths (channel 1) than at longer near-infrared wavelengths (channel 2). Conversely, atmospheric water vapor absorbs somewhat radiation in the channel 2 region, but has little influence on the transmission of radiation in the visible region. These atmospheric constituents tend to reduce the value of the NDVI (or of the SR), and their spatial and temporal variability render atmospheric corrections all the more necessary and difficult to implement on an operational basis.

We have assessed the effect of the atmosphere on the values of the SR and NDVI indices by investigating how the numerical value of these indices is transformed by the presence of the atmosphere. Figures 1 and 2 show the ratio of the values of SR and NDVI at the top of the atmosphere simulated with the parameterized atmospheric transfer model of Koepke (1989), over their values at the surface, for three typical atmospheres (clear, average, and moderately optically thick). From this particular example, it is seen that even a clear atmosphere significantly depresses the values of SR over deep canopies, and the values of NDVI over low vegetation cover. These atmospheric effects can, in principle, be taken into account if enough information is available on the state and composition of the atmosphere, and research is actively pursued in this direction (Chedin *et al.* 1989). This approach, however, requires the manipulation of large atmospheric data sets, and may consequently be difficult to implement on an operational basis.

We propose an alternate approach, which consists in deriving a different index, designed to minimize the relative influence of atmospheric effects. Searching for an index that would behave like SR over low vegetation and like NDVI over deep vegetation, it appeared that a non-linear combination of the channels or of SR would be required. This new index should have the following characteristics with respect to the atmospheric effects (1) a 'transmission', defined as the ratio of the vegetation index at the top of the atmosphere over its value at the surface, as high as possible (e.g., close to 1), (2) a 'transmission' as insensitive as possible with respect to the values of the

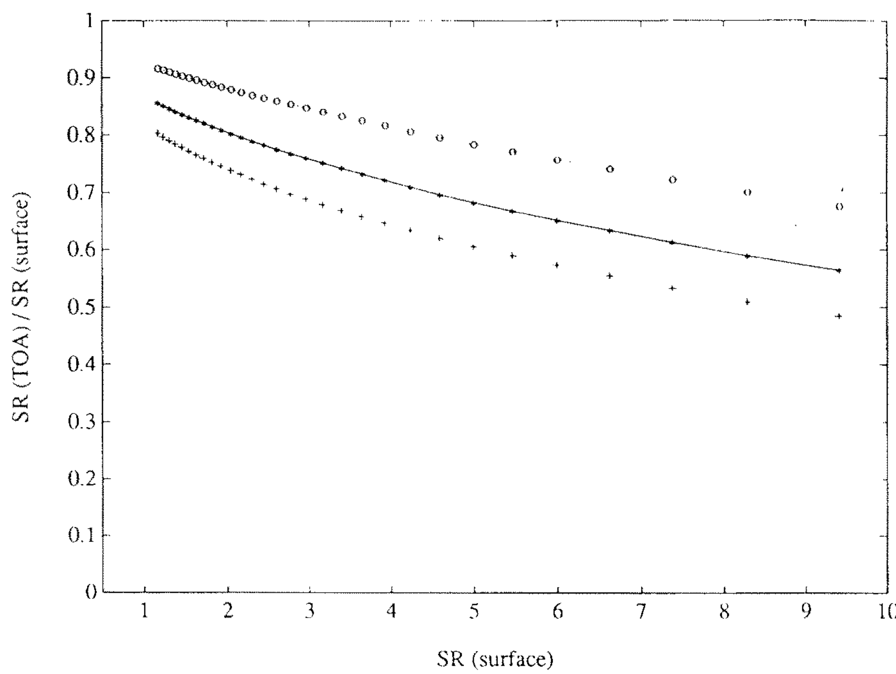

Fig. 1. Diagram showing the masking effect of the atmosphere on the information content carried by the Simple Ratio (SR) index. The three curves represent the ratio of the SR index at the top of the atmosphere (TOA) over the SR value at the surface, for a clear (o), average (*), and moderately thick atmosphere (+). The curves are given as functions of surface values of SR, generated by varying the channel 1 albedo from 0.068 to 0.30, and channel 2 albedo from 0.64 to 0.35. Solar illumination is set at 30°. The top of the atmosphere indices are computed on the basis of planetary albedos estimated from the surface values in both channels, for given atmospheric conditions, following the linearized scheme suggested by Koepke (1989). The clear atmosphere is characterized by an optical depth at 0.55 μm of 0.05, and a integrated water content of 0.5 cm. The corresponding values for the thick atmosphere are 0.3 and 4.0 cm, respectively.

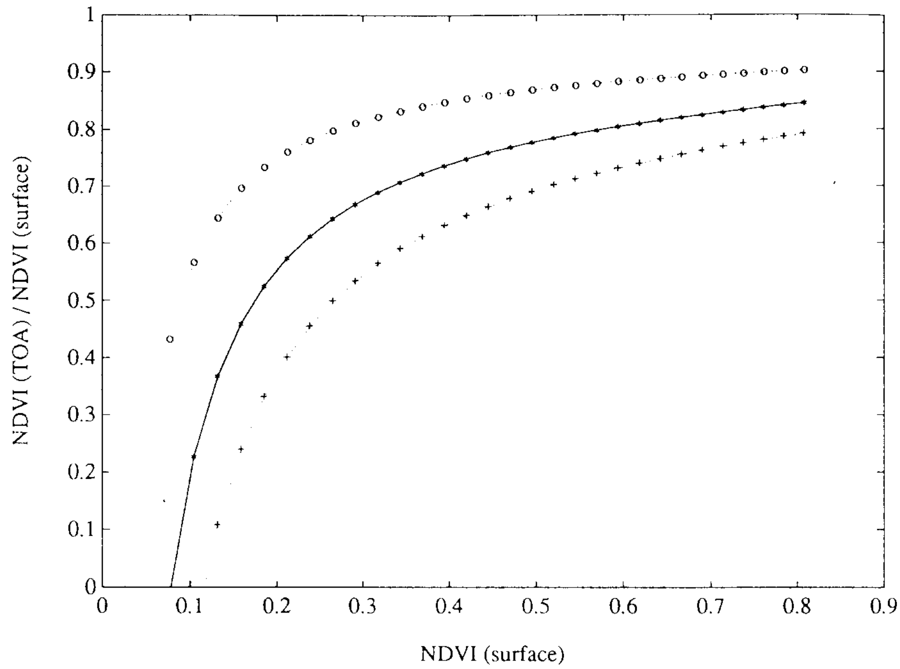

Fig. 2. Same as Figure 1, except for the Normalized Difference Vegetation Index (NDVI).

index, (3) a 'transmission' as insensitive as possible with respect to variations in the optical thickness of the atmosphere. This new index should of course (4) have a sufficiently large dynamic range, and (5) be empirically representative of surface vegetation cover in a manner comparable to SR or NDVI.

The non-linear index we propose, which satisfies reasonably well these requirements, is given by

$$\mathrm{GEMI} = \eta(1 - 0.25\,\eta) - \frac{\rho_1 - 0.125}{1 - \rho_1} \qquad (5)$$

where

$$\eta = \frac{2\,(\rho_2^2 - \rho_1^2) + 1.5\,\rho_2 + 0.5\,\rho_1}{\rho_2 + \rho_1 + 0.5}$$

This new index varies approximately between 0 and + 1 over continental areas, when SR ranges between 1 and large values, or when NDVI varies between 0 and + 1. Figure 3 shows the 'transmission' of this non-linear index through the same three atmospheres and for the same values of surface reflectance ρ_1 and ρ_2 used for Figure 1 and 2. From the comparison of Figures 1, 2 and 3, it is seen that GEMI (Global Environment Monitoring Index) complies better to the requirements expressed above than either SR or NDVI, over the entire range of vegetation values, and for all atmospheric conditions. It is seen that, when the atmospheric optical thickness increases from clear to more turbid conditions, the range of 'transmission' of SR and NDVI is larger than that of GEMI. Additional studies, to be reported on elsewhere, have shown that the biological information content of this index is at least as good as that of the NDVI.

Since a change in the solar zenith angle corresponds to a variation in optical path, the 'transmission' of this index is less affected than that of the other two linear indices by the illumination conditions. Hence, a greater part of the total variability can be attributed to the surface, and the remaining atmospheric effects contribute a smaller fractional part to the total signal. GEMI, computed from measurements at the top of the atmosphere, is therefore both (1) more useful to compare observations under varying atmospheric and illumination conditions, and (2) more repre-

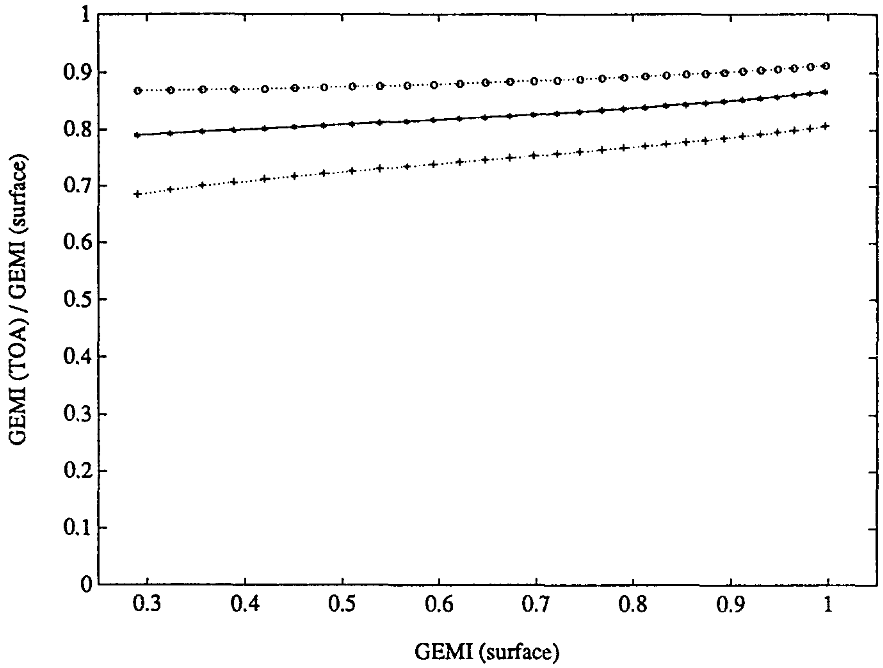

Fig. 3. Same as Figure 1, except for the new non-linear index GEMI.

sentative of actual surface conditions than SR or NDVI over the bulk of the range of vegetation conditions.

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