Sensitivity Analysis of Spectral Indices to Ozone Absorption Using Physical Simulations in a Forest Environment: Comparative Study between MODIS, SPOT VÉGÉTATION & AVHRR

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Abstract: Considering a forest cover (Balsam Fir with various densities) we analyze the sensitivity of several vegetation indices to ozone absorption using physical simulations in the spectral bands of MODIS, VEGETATION and AVHRR sensors. Except for the EVI, MSR and GARI, the results indicate that all the vegetation indices used in this study normalize the ozone absorption in particular TSARVI and GEMI. In addition, this study underlines the MODIS sensor contribution to minimize the ozone absorption effect.

1. Introduction

The processes of atmospheric diffusion by aerosols and molecules, and absorption by gases (ozone, water vapour and carbon dioxide) disturb terrestrial surface reflectance measurements acquired by optical satellites. When designing remote sensing sensors, the spectral bands are selected in order to avoid as much as possible encroaching on the absorption bands of atmospheric gases (Deschamps *et al.,* 1984). However, a relatively weak gas absorption effect always persists, which results in an attenuation of a few percentage of the reflectance measured at the sensor. In general, aerosol and molecule diffusion and water vapour absorption effects are corrected and removed from images before extracting information on land use. In the literature, we find a very rich and varied documentation demonstrating and explaining the effects of these two atmospheric components on optical remote sensing data (Deschamps *et al.,* 1984; Vermot *et al.,* 1996). Furthermore, investigations showing the impact of ozone absorption on the data or on the extraction of the biophysical parameters are rare.

Ozone is an important chemical component of the atmosphere. It occurs naturally in the atmosphere in small quantities as an unstable gas, but its levels are increasing at the surface as a result of human activities. The measured concentrations increase with altitude and are strong in forest environments. Ozone concentrations have been increasing in the atmosphere at a rate of approximately 1 % per year, with a strong dependence on the amount of sunlight and prone to strong inter-annual variations. The correction of optical remote sensing images for ozone should be based on actual measurements derived, for example, from the *Total Ozone Mapping Spectrometer* (TOMS) or other appropriate sensors (McPeters *et al.,* 1996). However, access and utilization of these data can be difficult. Using the concentration values from standard climatic tables with latitudinal and seasonal dependence is acceptable and is the most useful approach. In this study, we analyze the sensitivity of several vegetation indices to ozone absorption considering a forest cover (Balsam Fir) and using physical simulations. To achieve our goal, spectroradiometric measurements were acquired above a forest cover with various densities. All of the measurements were resampled and convolved in the solar-reflective spectral bands of the MODIS, VEGETATION and AVHRR sensors. The 6S (*Second Simulation of the Satellite Signal of the Solar spectrum*) atmospheric radiative transfer code was used with variable ozone concentrations and different forest cover density using the spectral bands of these three sensors.

2. Materials and Methods

2.1 Study Site and Ground Measurements

The study site is a forest area of the Cape Breton Island, News Scotland, Canada, 46°44'N, 60°40'O. The Western part of the site is in the National park of Prince Albert and the Eastern area is part of the provincial forest. It's an experimental zone used since 1976 for the development of remote sensing techniques and application in a forest environment. The site is composed mainly of a stand (Balsam Fir) plantation with different densities and various stages of maturity. In this study, spectroradiometric measurements were acquired above the forest canopy with various densities: 0, 25, 50, 70 and 100 percent. The measurements were carried out with a portable GER-3700 spectroradiometer (350 to 2500 nm). To take into account the bi-directional effect of the target reflectance, which depends both on the illumination angle and the viewing angle, we carried out measurements around the zenith hour following a vertical view direction. All of the spectroradiometric measurements were resampled and convolved in the solar-reflective spectral bands of the MODIS, VEGETATION and AVHRR sensors. Percent green cover was estimated from 35-mm slides obtained simultaneously from a camera mounted to the spectroradiometer.

Comment [CC1]: Saying the ozone is « the most significant chemical » in the atmosphere is a bit strong and does not sound very accurate (wouldn't oxygen be considered more important?)

2.2 Simulations conditions

In order to highlight the ozone absorption effects on the spectral bands (blue, green, red and near infrared) and, consequently, on the vegetation indices, the transfer radiative code 6S was used (Vermot *et al.,* 1996). An atmospheric model US-standard 1962 and an atmosphere without aerosols were considered. We fixed the view angle in the nadir and the solar angle at 45° with an azimuth angle at 30° and a view zenith angle at 0°. Simulations were carried out considering a forest cover with different densities: 0, 25, 50, 70 and 100 %. The used ozone concentrations were related to the following zones: tropical (0.247 g.cm-2), subarctic summer (0.346 g.cm-2), average latitudes in winter (0.395 g.cm-2) and subarctic in winter (0.48 g.cm-2). Furthermore, we used two extreme values of ozone contents corresponding to 0.495 g.cm3 and 0.959 g.cm3. These concentrations were programmed in the 6S code database. For each simulation, we considered the three sensors and various forests cover densities.

2.3 Spectral indices

Theoretically, the "ideal" vegetation index should be sensitive to vegetation cover, insensitive to soil background (color, brightness, moisture and roughness), independent of the spatial and spectral resolutions of the sensors, little affected by atmospheric and environment effects, does not saturate rapidly, normalize the drift of the sensor radiometric calibration, as well as solar illumination geometry and senor viewing conditions (Jackson *et al.,* 1983; Bannari,1996). These effects intervene simultaneously during *in situ* measurements and at the time of the satellite and/or airborne images data acquisition. In the literature, more than fifty vegetation indices (Bannari *et al.,* 1995) were developed for different applications and to correct some of these different problems. In this study we retain only those that are developed to minimize the soil and atmospheric effects.

The *Normalized Difference Vegetation Index* (NDVI) developed by Rouse *et al.* (1974) is the most popular index and the most used in various remote sensing applications. This index has undergone several transformations to minimize soil and atmospheric effects. By considering the bare soil line parameters, slope and origin, Richardson and Wiegand (1977) developed the *Perpendicular Vegetation Index* (PVI). However, Huete (1988) demonstrated that there was a contradiction between the NDVI and PVI indices in describing the spectral behaviour of vegetation and soil background. Consequently, he developed a new vegetation index called the *Soil Adjusted Vegetation Index* (SAVI), which is somewhat a compromise between ratio indices (NDVI) and orthogonal indices (PVI). The originality of this transformation lies in the establishment of a simple model, which describes adequately the soil-vegetation system. In order to reduce the soil color and brightness on the SAVI, Baret *et al.* (1989) proposed a new version of this index: the *Transformed Soil Adjusted Vegetation Index* (TSAVI). The soil line parameters (slope and origin) are introduced into the calculation of this index, which gives it a global character, i.e. it requires the use of only one index for different applications instead of using a determined index for each specific application (Baret *et al.,* 1989). To improve the sensitivity of SAVI to vegetation and to increase its potential to discriminate the bare soil, Qi *et al.* (1994) proposed a modified version: the *Modified Soil Adjusted Vegetation Index* (MSAVI). Rondeaux *et al.* (1996) adapted the TSAVI especially for agricultural applications in a new version named *Optimized Soil Adjusted Vegetation Index* (OSAVI). The OSAVI is a particular case of the TSAVI when the slope (a) and the origin (b) of soil line are equal to 1 and 0, respectively

In order to correct atmospheric diffusion on the NDVI, Kaufman and Tanré (1992) developed a new vegetation index: the *Atmospherically Resistant Vegetation Index* (ARVI). A self-correction process for the atmospheric effect on the red channel accomplishes the resistance of this index to atmospheric effects. The resistance degree of the ARVI to the atmospheric variations depends on the accuracy of the determination of the atmospheric self-correction coefficient. Based on the 5S code, Kaufman and Tanré (1992) recommend the unit value for self-correction coefficient ($\gamma = 1$) allow a better adjustment for most remote sensing applications; unless the aerosol model is known a priori. To correct the atmospheric effects on the TSAVI, Bannari *et al.* (1997) have proposed the *Transformed Soil Atmospherically Resistant Vegetation Index* (TSARVI). This transformation was based on the substitution of the red channel by the red-blue channel as suggested by Kaufman and Tanré (1992) and on the calculation of the bare soil line parameters (slope and origin) in the red-blue/NIR apparent spectral space. Developed especially for AVHRR sensor by using only apparent reflectances, the *Global Environment Monitoring Index* (GEMI) is a non-linear index. The objective of the GEMI is to evaluate and manage globally the environment without being affected by the atmosphere (Pinty and Verstraete, 1992). For a combined correction of the atmospheric effects and optical properties of soil background, Huete *et al.* (1996) proposed a new version of SAVI named the *Enhanced Vegetation Index* (EVI).

Theoretically, the values of the optimal vegetation index must be between 0 and 1, respectively, for bare soil and dense vegetation cover. However, because of the disturbances and the problems raised above, the perfect linearity is not obtained by any vegetation index (Bannari *et al.,* 2000). This problem is partially caused by the high sensitivity to the chlorophyll absorption in the red, which saturates very quickly (Huete *et al.,* 1999). In order to solve the linearity problem, Roujean and Breon (1995) proposed the *Renormalized Difference Vegetation Index* (RDVI). This index is a simple re-normalization of the NDVI in order to have a very good linear relationship to the surface biophysics parameters. As for the *Modified Simple Ratio* (MSR), it is an improved version of the RDVI for biophysical parameters extraction in boreal forest environment (Chen, 1996). To solve the linearity problem and to correct atmospheric effects, Gitelson *et al.* (1996) proposed the *Green Atmospherically Resistant Vegetation Index* (GARI), which exploits apparent reflectance in the blue, red, green, and near infrared channels.

$$NDVI=\frac{(\rho_{PIR}-\rho_{R})}{(\rho_{PIR}+\rho_{R})} \quad (1)$$

$$PVI=\frac{\rho_{PIR}-a\rho_{R}-b}{\sqrt{a^2+1}} \quad (2)$$

$$SAVI=\frac{\rho_{PIR}-\rho_{R}}{\rho_{PIR}+\rho_{R}+L}*(1+L) \quad (3)$$

$$OSAVI=\frac{(\rho_{PIR}-\rho_{R})}{(\rho_{R}+\rho_{PIR}+0{,}16)} \quad (4)$$

$$MSAVI=\frac{\left[2\rho_{PIR}+1-\sqrt{(2\rho_{PIR}+1)^2-8(\rho_{PIR}-\rho_{R})}\right]}{2} \quad (5)$$

$$TSAVI=\frac{\left[a\left(\boldsymbol{\rho}_{PIR}-a\boldsymbol{\rho}_{PIR}-b\right)\right]}{\left[\left(\boldsymbol{\rho}_{R}+a\boldsymbol{\rho}_{PIR}-ab+0{,}08\left(1+a^{2}\right)\right)\right]} \quad (6)$$

$$ARVI=\frac{(\rho^{*}_{PIR}-\rho^{*}_{RB})}{(\rho^{*}_{PIR}+\rho^{*}_{RB})} \quad (7)$$

$$TSARVI=\frac{\left[a_{rb}\left(\boldsymbol{\rho}^{*}_{PIR}-a_{rb}\boldsymbol{\rho}^{*}_{RB}-b_{RB}\right)\right]}{\left[\boldsymbol{\rho}^{*}_{RB}+a\boldsymbol{\rho}^{*}_{PIR}-a_{rb}b_{rb}+0{,}08\left(1+a^{2}_{rb}\right)\right]} \quad (8)$$

With: $\rho^{*}_{PIR}=a_{rb}\rho^{*}_{RB}+b_{rb}$

$$\rho^{*}_{RB}=\rho^{*}_{R}-\gamma\left[\rho^{*}_{B}-\rho^{*}_{R}\right]$$

$$\gamma=\frac{\rho_{a-r}}{\left[\rho_{a-b}-\rho_{a-r}\right]}$$

$$GEMI=\boldsymbol{\eta}(1-0{,}25\boldsymbol{\eta})-\frac{(\boldsymbol{\rho}^{*}_{R}-0{,}125)}{(1-\boldsymbol{\rho}^{*}_{R})} \quad (9)$$

With: $\boldsymbol{\eta}=\frac{\left[2\left(\boldsymbol{\rho}^{*2}_{PIR}-\boldsymbol{\rho}^{*2}_{R}\right)+1{,}5\boldsymbol{\rho}^{*}_{PIR}+0{,}5\boldsymbol{\rho}^{*}_{R}\right]}{\left(\boldsymbol{\rho}^{*}_{PIR}+\boldsymbol{\rho}^{*}_{R}+0{,}5\right)}$

$$EVI=\frac{2{,}5\left(\boldsymbol{\rho}_{PIR}-\boldsymbol{\rho}_{R}\right)}{\left(L+\boldsymbol{\rho}_{PIR}+6\boldsymbol{\rho}_{R}-7{,}5\boldsymbol{\rho}_{B}\right)} \quad (10)$$

$$RDVI=\frac{(\rho_{PIR}-\rho_{R})}{\sqrt{\rho_{PIR}+\rho_{R}}} \quad (11)$$

$$MSR=\frac{\frac{\rho_{PIR}}{\rho_{R}}-1}{\sqrt{\frac{\rho_{PIR}}{\rho_{R}}+1}} \quad (12)$$

$$GARI=\frac{\left\{\rho^{*}_{PIR}-\left[\rho^{*}_{Vert}-\lambda\left(\rho^{*}_{B}-\rho^{*}_{R}\right)\right]\right\}}{\left\{\rho^{*}_{PIR}-\left[\rho^{*}_{Vert}+\lambda\left(\rho^{*}_{B}-\rho^{*}_{R}\right)\right]\right\}} \quad (13)$$

Where:
ρ_R : ground reflectance in the red channel,
ρ_{PIR} : ground reflectance in the near infrared red channel,
ρ_B : ground reflectance in the blue channel,
ρ^*_B : apparent reflectance in the blue channel,
ρ^*_V : apparent reflectance in green channel,
ρ^*_R : apparent reflectance in the green channel,
ρ^*_{PIR} : apparent reflectance in the near infrared channel,
ρ^*_{RB} : apparent reflectance in the red-blue channel,
ρ_{a-r}: atmospheric reflectance in the red channel,
Δ_{a-b}: atmospheric reflectance in the blue channel,
γ : atmospheric self-correction factor,
a and b : slope and ordinate at the origin of the bare soil in the red/NIR spectral space,
a_{rb} and b_{rb} : slope and ordinate at the origin of the bare soil in the red-bleu/NIR apparent spectral space,
L : soil adjustment factor, equal to 0.5.

3. Results and Discussions

Although atmospheric ozone component absorb the electromagnetic radiation in certain wavelengths, the design and the conceptualization of vegetation indices never considers this effect. Considering the channels of MODIS, VEGETATION and MODIS sensors, the reflectance analysis shows that the ozone absorption decreases the reflectance in the near infrared in the same way as the water vapour absorption. However, when the ozone concentration increases in the atmosphere, the values of the vegetation indices decrease. This effect cannot be neglected especially for the indices derived from the broadband AVHRR sensor. Considering different situations, different ozone concentration and different vegetation indices, the figure 1 illustrate the sensitivity of each vegetation index to the ozone absorption and potential of MODIS sensor to normalize very well the ozone absorption effect.

The obtained results show us that the MSR is most sensitive index to the ozone absorption. Compared to ground truth, the relative error is approximately 23% for AVHRR, 20 % for VEGETATION and 16% for MODIS. Moreover, this index is the most sensitive to the atmospheric diffusion and water vapour absorption (Bannari *et al.,* 2000). Consequently, the MSR cannot be used for temporal change detection of the forest cover and land use without atmospheric correction.

The EVI sensitivity to the ozone absorption is much lower in comparison with its sensitivity to the water vapour absorption or the aerosols diffusion (Asalhi, 2003). For an extreme ozone concentration (UO3 = 0,959 g.cm3), the relative error on this index is 19 % for VEGETATION and MODIS sensors. Furthermore, the GARI behaviour varies largely according to the value of the atmospheric self-correction coefficient and the density of vegetation cover. This index is so resistant to the ozone absorption when it is calculated with a self-correction coefficient equal to 0.5 and a very dense vegetation cover, the error is approximately 7 %. However, when the vegetation cover decreases, the relative error increases to 15% for a bare soil.

When we consider a dense forest cover with an extreme ozone concentration (UO3 = 0,959 g.cm3), the relative error on the PVI reaches 15 % for AVHRR, 8 % for VEGETATION and it does not exceed 4% for MODIS. Contrary to the GARI, when the vegetation becomes sparse, the relative error decreases drastically on the PVI. Thus, for a 50 % forest cover density; the error on the PVI reaches 8 % for AVHRR, 5 % for VEGETATION, whereas the error remains lower than 1 % for MODIS.

The MSAVI shows a very good resistance to the ozone concentration variations particularly for MODIS sensor. Indeed, considering the broadband AVHRR sensor, the error on the MSAVI is 14% when the cover is very dense and is 7% for a moderate density. If we consider these two cover rates, the relative error on this index is 10 % and 5% for VEGETATION. The spectral resolution of MODIS sensor offers a better precision; the relative error is 6 % for a very dense cover and 2 % for a fairly dense cover.

For the indices that adjusted to the bare soils (SAVI, TSAVI, OSAVI and RDVI), they show the same sensitivity to the ozone concentration variations. This sensitivity decreases significantly when we use the MODIS spectral resolution. Considering a very dense forest cover, for the TSAVI, the

relative error is 11 %, 9 % and 5 % for AVHRR, VEGETATION and MODIS, respectively. However, RDVI, OSAVI and SAVI indices show a similar sensitivity in the bands of the same sensor. Indeed, relative error is 9% for AVHRR, 7 % for VEGETATION and 4 % for MODIS.
With the difference of the four preceding indices, the NDVI shows a similar relative error between AVHRR and VEGETATION. In the extreme ozone concentration and a very dense cover, the relative error on the NDVI is 8 %. If we consider the same conditions, we show that the MODIS bands normalize better the ozone absorption effect on this index; the relative error does not exceed 4%.
The indices developed to correct the atmospheric effects (ARVI and TSARVI) normalize correctly the variations of the ozone concentration in the atmosphere. In the extreme ozone concentration (0,959 g/cm3) and a very dense forest cover, the relative error on the ARVI ($\gamma = 0.5$) does not exceed 7 % independently from the sensor characteristics. In the same condition, the relative error on the TSARVI ($\gamma = 0.5$) does not exceed 5 % and 3 %, respectively, for VEGETATION and MODIS. We can conclude that the TSARVI index is the least affected by the atmospheric effects. Also, GEMI index has a low sensitivity to the ozone absorption effect. For a dense cover and strong ozone concentration in the atmosphere, the relative error on this index is 6 %, 2 % and 1% for AVHRR, VEGETATION and MODIS, respectively. According to Asalhi (2003) and Bannari *et al.* (2000), the GEMI is less sensitive to the water vapour absorption and resistant to the aerosols diffusion.

4. Conclusions

Figure 1 summarizes the impact of a strong ozone concentration (0,959 g/cm3) on different vegetation indices considering a very dense forest cover (100 %). Except for the EVI, MSR and GARI, all used vegetation indices are characterized in general by a good resistance to the ozone absorption particularly in MODIS channels. This sensor seems to avoid perfectly the ozone absorption bands. Furthermore, the relative error is higher for the AVHRR sensor and relatively higher for the VEGETATION sensor. In the broadband AVHRR sensor, the relative errors vary between 6 % and 23% for the most resistant (GEMI) and the most sensitive index (MSR). Also, this figure underlines the perfect resistance of the TSARVI and GEMI to the ozone absorption considering the MODIS and VEGETATION sensors.

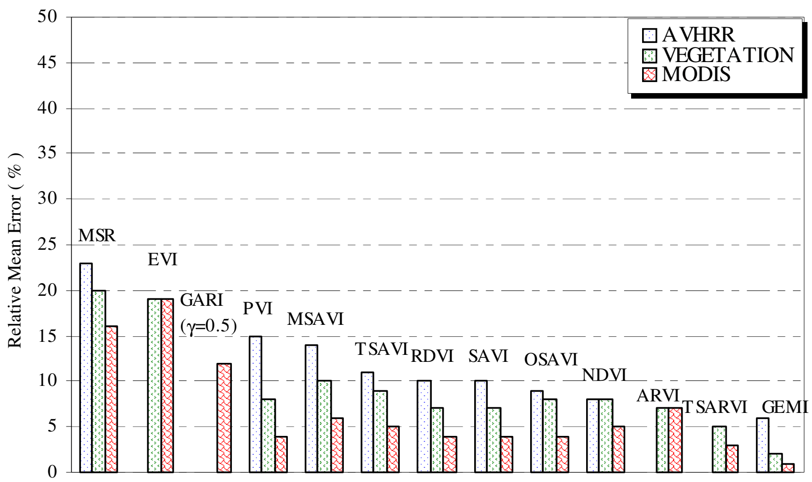

Figure 1: Sensitivity of different vegetation indices to ozone concentration (0,959 g/cm3) considering a dense forest cover (100 %).

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