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Y. J. Kaufman
National Atmospheric and Space Administration, USA

D. Tanré
Université de Sciences et Techniques de Lille

B. N. Holben
National Atmospheric and Space Administration, USA

B. L. Markham
National Atmospheric and Space Administration, USA, brian.l.markham@nasa.gov

Anatoly A. Gitelson
University of Nebraska - Lincoln, agitelson2@unl.edu

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ATMOSPHERIC EFFECTS ON THE NDVI - STRATEGIES FOR ITS REMOVAL

Y.J. Kaufman[1], D. Tanré[2], B. N. Holben[1], B. Markham[1] and A. Gitelson[3]
[1]*NASA/Goddard SFC, Greenbelt, MD 20771*
[2]*Laboratoire d'Optique Atmospherique, Université de Sciences et Techniques de Lille, Villeneuve d'Ascq, France*
[3]*Inst. for Desert Res., Ben Gurion Univ., Sde-Boker, Israel*

ABSTRACT

The compositing technique used to derive global vegetation index (NDVI) from the NOAA-AVHRR radiances, reduces the residual effect of water vapor and aerosol on the NDVI. The reduction in the atmospheric effect is shown using a comprehensive measured data set for desert conditions, and a simulation for grass with continental aerosol. A statistical analysis of the probability of occurrence of aerosol optical thickness and precipitable water vapor measured in different climatic regimes is used for this simulation. It is concluded that for a long compositing period (e.g. 27 day), the residual aerosol optical thickness and precipitable water vapor is usually too small to be corrected for. For a 9 day compositing the residual average aerosol effect may be about twice the correction uncertainty. For Landsat-TM or EOS-MODIS data, the newly defined atmospherically resistant vegetation index (ARVI) is more promising than possible direct atmospheric correction schemes, except for heavy desert dust conditions.

Introduction

Atmospheric effects on remote sensing of the earth's surface result from scattering and absorption of direct or reflected sunlight by atmospheric gases (e.g. water vapor and ozone) and aerosol particles (e.g. sulfate particles, dust and smoke). The vegetation index derived from the NOAA-AVHRR data is defined as the difference between channel 2 (0.84 μm) and channel 1 (0.64 μm), normalized by their sum [15]. For review of the atmospheric effects and correction algorithms see Tanré et al. [14]. Aerosol particles usually cause an increase in the radiance in channel 1 and a mixed effect in channel 2, resulting in a lower vegetation index. Water vapor reduces the apparent reflectance measured in channel 2, thus also reducing the vegetation index. The effect of molecular scattering and ozone absorption won't be discussed here, since their effect can be easily corrected for [5], [14].

Global vegetation index derived from the AVHRR 4 km resolution data, are based on a weekly or monthly composite of the vegetation index, where for each pixel the maximum value for the period is used [2]. This process minimizes the effect of clouds [6], aerosol and water vapor on the index. As a result of the compositing process, the average aerosol and water vapor amount that affect the derived vegetation index maps is lower from the climatological average. Since each of the atmospheric correction techniques has its accuracy limitations, it is important to establish what is the residual atmospheric effect after the compositing process and whether it is large enough so that application of corrections can significantly improve the vegetation index. This analysis is the subject of the present study.

Effect Of The Compositing Process On The Ndvi

In the compositing process the maximum NDVI is derived for a period of N days. Assuming that the atmospheric conditions are independent in each day, and that the cloud fraction, the aerosol optical thickness and the precipitable water vapor are uncorrelated, then we can say that some number of days, n_c, out of the N days is used to eliminate the effect of clouds, n_w to reduce the effect of water vapor and n_a to reduce the effect of aerosol. In computing the values of n_i (where i=c, w or a) the effect of surface and atmospheric angular reflectance has also to be considered. As a result we should expect that $n_a+n_c+n_w<N$. The fraction n_i also may depend on whether there is a correlation between the concentration of water vapor and aerosol particles in the atmosphere. From simultaneous measurements of water vapor and aerosol optical thickness in the Sahel [4] the correlation coefficient between optical thickness and precipitable water vapor was found to be only 0.5.

The statistical dependence of the aerosol optical thickness, τ, on time may vary from one geographical region to another due to a different combination of sources, transport, aerosol aging processes and sinks. Therefore, in order to pose the question: what is the lowest value of τ for 1 out of n_a values, some simplification of the problem is required. Figure 1 shows several statistical measurements of the distribution of aerosol optical thickness in several different conditions. The aerosol optical thickness, normalized by its average value of each data set, τ_a, is plotted as a function of the cumulative probability of occurrence. For cumulative probability of 0.1, 90% of the measurements are above the given normalized optical thickness value and 10% are below that value. The data sets cover several continents, all seasons and several aerosol types. The results are very similar for all the data sets, showing (subject to the representability of these data sets) that the probability of occurrence of a given normalized optical thickness is pretty universal. The differences between the curves are due to:

- errors in calibrations between the instruments,
- effect of persistent high relative humidities for some data sets,
- the presence of stratospheric aerosol due to the Mount Penetubo eruption (and affecting the GSFC data).

To compute the calibration error we assume that the instruments had stable calibrations, but an error in the absolute calibration that varies among the instruments. As a result (for a constant air-mass), the measurements are off by an error of $\Delta\tau$ which is constant in time but different for each instrument. The error $\Delta(\tau/\tau_a)$ associated with $\Delta\tau$ can be computed as the difference between the "true" value of $\Delta(\tau/\tau_a)$ and the measured value of $\Delta(\tau/\tau_a)$:

$$\Delta\left(\frac{\tau}{\tau_a}\right) = \frac{\tau+\Delta\tau}{\tau_a+\Delta\tau} - \frac{\tau}{\tau_a} \sim \frac{\Delta\tau}{\tau_a}\left(\frac{\tau}{\tau_a} - 1\right)$$

Assuming that $\Delta\tau$~0.02, the error is $\Delta(\tau/\tau_a)$=0.08 for fig. 1a and 0.03 for fig 1b, which represents most of the uncertainty in the figure.

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To illustrate the significance of this figure, take an example where 4 days are used to minimize the effect of aerosol on the vegetation index, $n_a=4$. In this case the median optical thickness for the data sets of Fig. 1 is obtained for the center of the lowest quarter or cumulative probability of occurrence, P, of $P_{av}=1/8$, which, excluding the stratospherically affected data yields: $\tau/\tau_{av}=0.20\pm0.05$. For $\tau_{av}=0.1$ to 0.3, as is in the case of Fig. 1a, one gets: $\Delta\tau=0.02$-0.06 and $\Delta\tau=0.12$ for Fig. 1b.

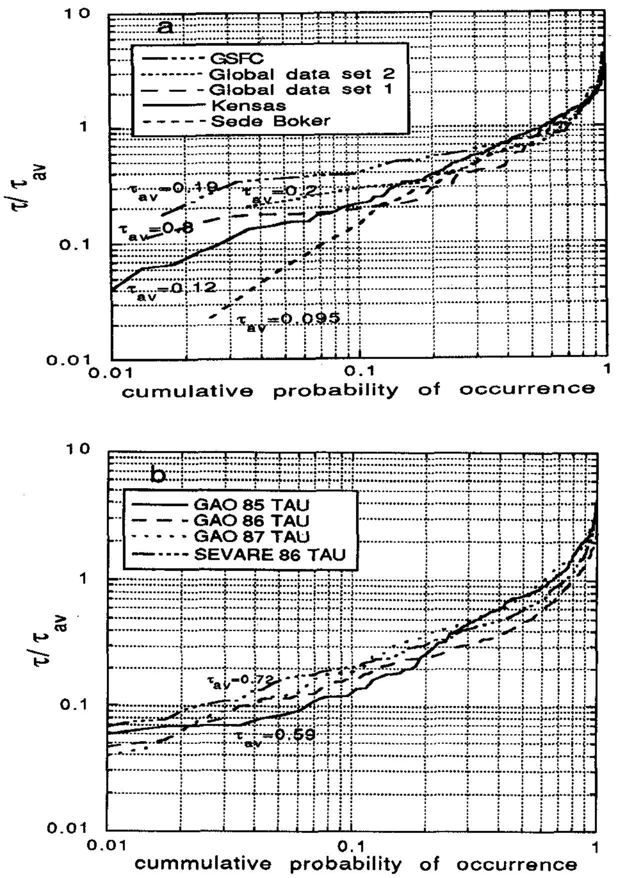

Fig. 1: The aerosol optical thickness (τ) normalized by its average value (τ_a) as a function of the cumulative probability of occurrence. (a) - global data sets of Kaufman [7], data set collected from Kansas during 1987-1989, data set collected from a desert site in Sede Boker, Israel and a data set from GSFC, Greenbelt, MD during 1991. (b) - 4 data sets collected in the Sahel during 1985-1987 [4].

Same analysis is applied to the precipitable water vapor (Fig. 2). In this case, for $n_w=4$ the median precipitable water vapor is 40% of the average amount of water vapor.

Examples of Applications

In order to assess the effective values of τ/τ_{av} and w/w_{av} that affect the derived vegetation index, we shall consider two examples: an arid region in Senegal and tropical forest in Brazil.

1. Desert terrain.

Soufflet et. al., [12] collected AVHRR radiances in the 2 solar bands (0.64 μm and 0.83 μm) simultaneous to measurements of the dust optical thickness and precipitable water vapor [13]. This data set can be used to assess the atmospheric effect on the composite vegetation index.

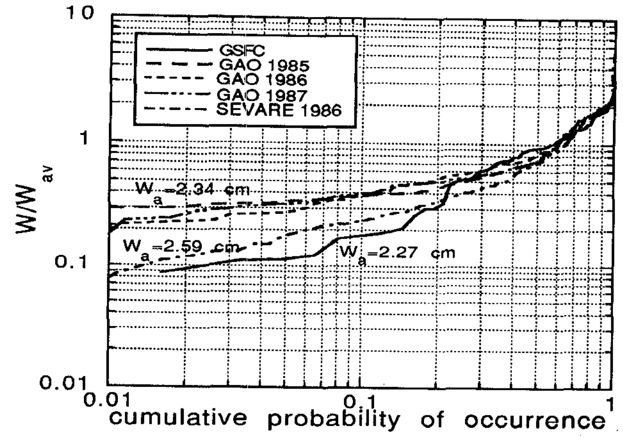

Fig. 2 The precipitable water vapor normalized by its average value (W_a) as a function of the cumulative probability of occurrence for the data sets collected in the Sahel [4] and in GSFC, Greenbelt MD.

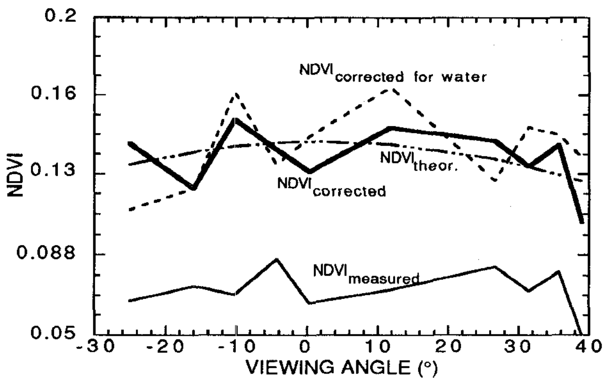

Fig. 3: The vegetation index over Senegal from AVHRR data collected during 9 cloud free days by Soufflet et al., [12] simultaneously to ground measurements of the aerosol optical thickness and precipitable water vapor. The measured NDVI (thin solid line) is corrected for the aerosol and water vapor effect (Thick solid line) and compared with a bidirectional model of Minnaert [11]. Partially corrected data for the water vapor effect only are also shown (dashed line).

The measured and corrected vegetation indexes from AVHRR data collected during 9 days over Senegal [12] are shown in Fig. 3. Since clouds are excluded from the analysis, the 9 days correspond to $9=n_a+n_w$. In this case the bidirectional effect is small and the highest measured NDVI occurs for view angle of -4°. This NDVI corresponds to the second lowest precipitable water vapor (0.67 cm out of an average of 1.8 cm of water). The aerosol optical thickness in this case is above average for the period (1.3 for an average of 0.9). The strong selection of minimum water vapor and weak influence of aerosol results from the high surface reflectances in this case (corrected surface reflectance of 0.24 in channel 1 and 0.31 in channel 2), the aerosol effect is small, sometimes reducing and sometimes increasing the NDVI, depending on the aerosol properties and the interaction of water vapor with aerosol. Therefore the atmospheric effect for desert conditions is dominated by the water vapor absorption.

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2. Vegetated region

In the case of vegetation, the atmospheric effect is dominated by aerosol scattering [14]. In the absence of an appropriate experimental data set, a simulation study is reported. In this simulation the AVHRR observations of a Fescue grass are simulated. The surface bidirectional reflectance and the atmospheric effect are taken from Holben et al., [2] and interpolated to typical AVHRR viewing directions (-53°, -44°, -33°, -19°, 8°, 23°, 36°, 47°, 55°). The surface reflectance varies from 0.049 and 0.31 in the two AVHRR bands respectively at nadir, to 0.090 and 0.60 at the backscattering direction. This strong angular dependence is not reflected very well in the vegetation index that varies only between 0.742 and 0.739 for the same view directions, and reaches 0.765 in the forward scattering direction.

For each observation, values of the aerosol optical thickness and the precipitable water vapor were selected randomly, so it generally fits the statistical distributions shown in Fig 1 and 2. The range of the optical thickness was chosen between 0.0 and 0.5 and that of water vapor between 0.0 and 5.0 cm. The upward radiance was first interpolated/extrapolated between the two aerosol models used by Holben et al., [3] for τ_a=0.1 and 0.5 and the amount of water vapor (W) was adjusted assuming that the transmission due to water vapor absorption (T_w) is $\ln T_w \propto \sqrt{W}$. The cloud cover was assumed to be complete (NDVI=0) or not existent, and was introduced by a random number so that the average cloud cover is 50%.

2754 AVHRR observations were simulated and the maximum NDVI for a period of N days (9 or 27) was systematically chosen. The aerosol optical thickness, the precipitable water vapor and the view direction that correspond to this maximum were recorded. Fig. 4 gives an example of several 9 day cycles, the values of the NDVI, optical thickness and precipitable water vapor. The selected values are indicated. The reduction in the residual values of τ_a and W as a function of the compositing period N are shown in Fig. 5. For a compositing period of 27 days, a relation is shown between the value of τ_a for the chosen NDVI's for N=27 and the average optical thickness for the 27 day period (Fig. 5a). For a compositing period of 9 days the average of three values of τ_a that correspond to the highest NDVI for three compositing periods are also plotted. In most cases the optical thickness for the composite NDVI is much lower than the average optical thickness, and that for N=27 lower than that for N=9. The average values are tabulated in Table 1. Relation between the average precipitable water vapor and the value that affects the composite NDVI is shown in Fig. 5b, with similar conclusions. In this case the effect of the composite on reduction of the aerosol burden is similar to that of water vapor.

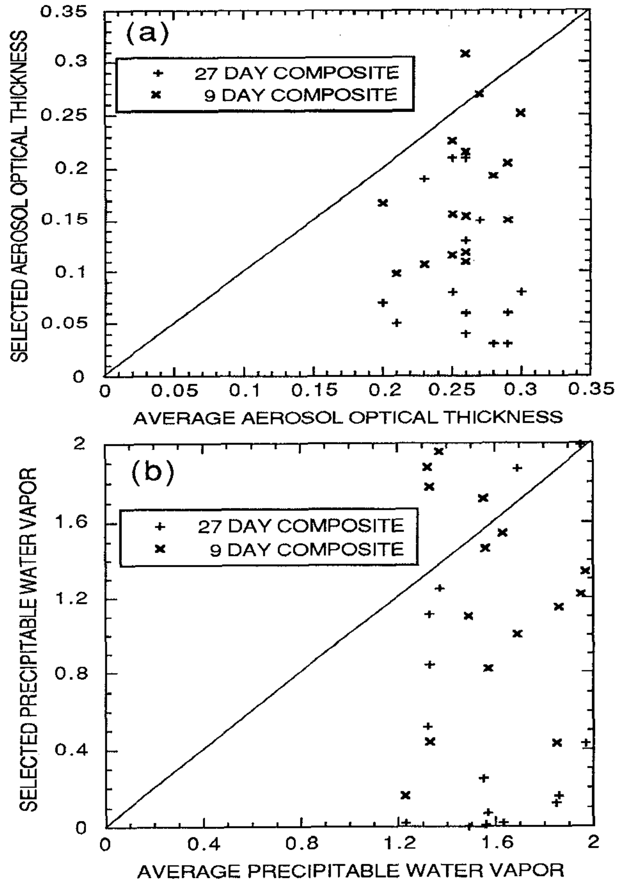

Fig. 5: (a)-Simulation for the relation between the average optical thickness for 27 days (3 AVHRR cycles) of observations and the optical thickness that affect the composite NDVI. (b)- same as (a) but for precipitable water vapor.

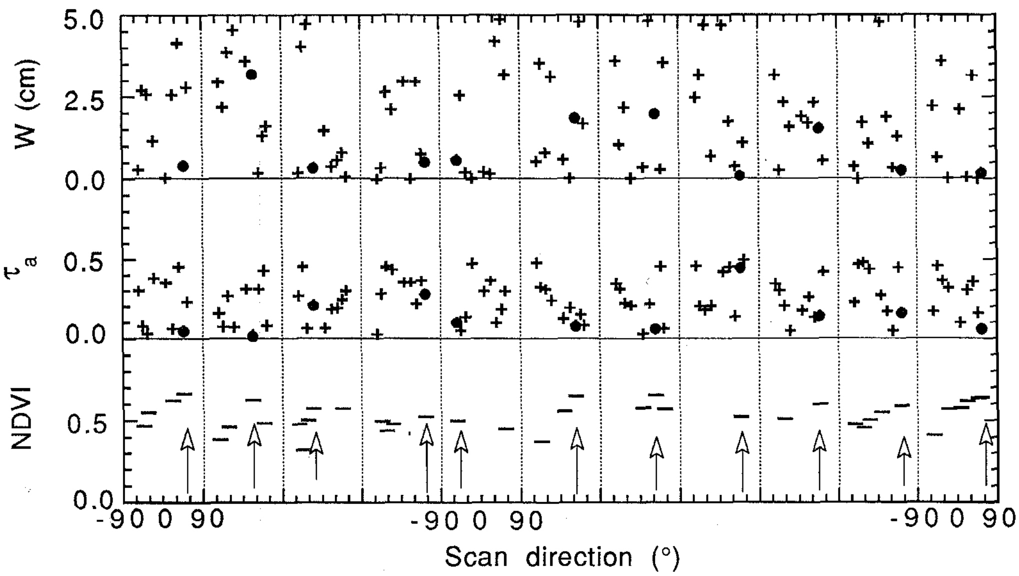

Fig. 4: The NDVI, the aerosol optical thickness, τ_a, and the precipitable water vapor, W, as a function of the view direction. The arrows indicate the selected NDVI for each cycle, and the corresponding values of τ_a and W are indicated by a heavier symbol. Note that the presence of clouds eliminated some of the NDVI values.

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Table 1: Average values of the view direction (θ), aerosol optical thickness (τ), precipitable water vapor (W) and the NDVI for no compositing (N=1), for compositing periods of N=9 and N=27 days. For each composite period the averages are given for the days where the maximum NDVI was recorded. Note that for N=1 there is no cloud screening.

N\parameter	NDVI	τ	W	θ
1	0.26±0.27	0.26±0.13	1.64±1.5	2.2°±38°
1 no clouds	0.53±0.08	0.26±0.13	1.64±1.5	2.2°±38°
9	0.61±0.046	0.17±0.12	1.27±1.4	25°±25°
27	0.65±0.027	0.12±0.09	0.86±1.3	33°±14°

Strategies for NDVI Correction

Correction for the aerosol effect

The correction schemes have an accuracy that corresponds to an uncertainty in the aerosol optical thickness of $\Delta\tau_a \approx \pm 0.1$ [5], [8]. Therefore, for the present examples, that show two typical cases, the utility of atmospheric correction of the composite NDVI is questionable. For N=27 the correction error is similar to the residual atmospheric effect over vegetation. The atmospheric effect over the desert area is small even though the aerosol optical thickness is large due to the high reflectivity of the surface [1]. For N=9 the residual atmospheric effect for the Fescue grass is about twice the correction uncertainty, and atmospheric correction has the potential to improve the NDVI. Note that even though for N=27 the average residual aerosol effect is within the accuracy of the correction methods, it may be still worthwhile to correct the cases with high residual optical thickness (e.g. the 4th cycle in Fig. 4). In some regions (e.g. Eastern US in the summer) the optical thickness is twice as large as in the examples used in this work, and correction should be applied.

Due to the limited utility of atmospheric correction for the global composite NDVI a different approach to reduce the atmospheric contamination was suggested for satellite data that include a channel in the blue part of the solar spectrum [9]. By defining the vegetation index differently, the radiance in the blue channel, that is strongly affected by atmospheric scattering, is used inherently to reduce the atmospheric effect in the red channel. The resultant Atmospherically Resistant Vegetation Index (ARVI) was shown, in a sensitivity study, to be 2-5 times less sensitive to atmospheric effects. If experimental verifications won't alter significantly these results, then based on the examples shown above, there will be no value in additional atmospheric corrections for the ARVI.

Correction for the water vapor

The residual precipitable water vapor of 1.1 cm for 9 day composite and 0.7 cm for 27 day composite, leaves a similar room of improvement as that for the aerosol effect. No direct method for inherent correction of the vegetation index for the influence of water vapor was suggested. The best strategy to eliminate the influence of water vapor is to design sensors with vegetation channels that are not affected by water vapor (e.g. MODIS on the EOS - [10]).

Conclusions

The compositing process in the generation of global NDVI maps reduces substantially the residual effect of tropospheric aerosol and water vapor on the NDVI. Simulations show that over a vegetated terrain the residual-aerosol and water vapor effect is twice as large as possible errors in a correction scheme for a composite of 9 days, and similar to the correction errors for composite period of 27 days. For example for Fescue grass compositing reduced the uncertainty in the NDVI due to aerosol and water vapor from standard deviation of ΔNDVI=±0.08 to ±0.05 for 9 day composite and ±0.03 for 27 day composite. In the EOS era, the water vapor free MODIS data are expected to reduce the residual aerosol optical thickness further. Therefore, while for the AVHRR atmospheric corrections are still important for short compositing periods and in areas with large aerosol, water vapor or cloud contamination, in the EOS-MODIS era the removal of the atmospheric effect from the composite NDVI would preferably utilize atmospherically resistant parameters (e.g. ARVI - [9]), rather than direct correction methods, except for heavy dust loading. Note that the present simulations assumed a random occurrence of values of aerosol optical thickness and precipitable water vapor. We did not study the effect of slow seasonal trends, that in some cases may make atmospheric corrections more beneficial. More realistic simulations can be based on a series of daily observations of the aerosol and water vapor loading and the presence of clouds. In the future we plan to collect such observations with networks of automatic sunphotometers that will record continuously the aerosol optical thickness and properties, precipitable waterwater vapor and the presence and thickness of clouds.

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