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C. Jamet, C. Moulin, S. Thiria. Monitoring aerosol optical properties over the Mediterranean from SeaWiFS images using a neural network inversion. *Geophysical Research Letters*, 2004, 31 (13), pp.n/a-n/a. 10.1029/2004GL019951 . hal-03130148

HAL Id: hal-03130148

<https://hal.science/hal-03130148>

Submitted on 3 Feb 2021

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Monitoring aerosol optical properties over the Mediterranean from SeaWiFS images using a neural network inversion

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Received 11 March 2004; revised 12 May 2004; accepted 14 June 2004; published 15 July 2004.

[1] The SeaWiFS archive provides a unique opportunity to study aerosol optical properties over oceans since October 1997. Standard SeaWiFS aerosol products are however not suitable because optical thicknesses are limited to 0.35 and Angström exponents to 1.5. We developed an inversion based on neural networks to retrieve both optical thickness and Angström exponent from SeaWiFS red and near infrared channels. Neural networks are capable of approximating non-linear inverse functions and of processing efficiently large amounts of data. Neural networks were trained with radiative transfer computations for wide ranges of optical thickness and Angström exponent. All SeaWiFS images of the Mediterranean for year 2000 were processed and monthly mean maps of aerosol optical thickness and Angström exponent were derived. A comparison with ground-based measurements at three AERONET stations in the Mediterranean shows the good accuracy of the method, as well as the improvement compared to operational SeaWiFS aerosol products. **INDEX TERMS:** 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0394 Atmospheric Composition and Structure: Instruments and techniques; 4801 Oceanography: Biological and Chemical: Aerosols (0305). **Citation:** Jamet, C., C. Moulin, and S. Thiria (2004), Monitoring aerosol optical properties over the Mediterranean from SeaWiFS images using a neural network inversion, *Geophys. Res. Lett.*, 31, L13107, doi:10.1029/2004GL019951.

1. Introduction

[2] Both natural and anthropogenic aerosols play an important role in climate forcing. They do not only directly influence radiative transfer in the atmosphere, but they also indirectly affect the Earth radiative budget by providing cloud condensation nuclei and increasing cloud formation. Satellite imagery is suitable to monitor aerosol optical thicknesses at the global scale [Kaufman *et al.*, 2002], and long time-series of images from Meteosat and TOMS have recently been used to study both seasonal and inter-annual variability of mineral dust transport over the last 20 years [Chiapello and Moulin, 2002; Moulin and Chiapello, 2004]. These meteorological sensors were however not designed for aerosol studies and they do not allow to determine important aerosol optical properties such as the Angström exponent, which characterizes the aerosol size distribution.

[3] More recent sensors with multi-spectral capabilities (e.g., SeaWiFS, MODIS and POLDER) enable to retrieve various aerosol parameters over the ocean [Gordon and Wang, 1994; Tanré *et al.*, 1997; Deuzé *et al.*, 2000], including the Angström exponent. The SeaWiFS ocean color sensor provides multispectral measurements in the visible and near infrared (NIR) spectrum since October 1997. SeaWiFS aerosol products (i.e., aerosol optical thickness and Angström exponent) are generated, validated and made available by NASA [Wang *et al.*, 2000]. These aerosol products remain however a by-product of the atmospheric correction algorithm and are hardly usable for global aerosol studies mainly because aerosol optical thicknesses higher than about 0.35 are rejected to ensure the quality of the marine parameters, preventing from observing dense aerosol plumes.

[4] The SeaWiFS aerosol products have other drawbacks, which are related to the atmospheric correction algorithm itself [Gordon and Wang, 1994]. This algorithm is time-consuming because it relies on a comparison of SeaWiFS measurements in the NIR (i.e., 765 and 865 nm) to theoretical values computed for several types of aerosols. Another important limitation of this method for aerosol studies is that retrieved Angström exponent values are confined between 0 and 1.5 by construction, whereas its actual range is rather between 0 and 2, as shown by sun-photometer measurements in coastal areas [Holben *et al.*, 2001]. This suggests that SeaWiFS aerosol products do not provide relevant information where small aerosols (i.e., characterized by large Angström exponent), dominate. We present here the results of a new method that is fast and accurate enough to reprocess large sets of SeaWiFS images for aerosol studies.

2. Method

[5] Neural networks (NN) are good candidates for modeling inverse functions in geophysical applications [Thiria *et al.*, 1993]. Here we use a particular class of NN, the so-called Multi-Layered Perceptron, MLP [Bishop, 1995], to retrieve independently the aerosol optical thickness at 865 nm, $\tau(865)$, and the Angström exponent between 510 and 865 nm, $\alpha(510)$, from SeaWiFS measurements in the red (670 nm) and near infrared (765 and 865 nm) bands. The Angström exponent between 510 and 865 nm was chosen for compatibility with standard SeaWiFS products. An MLP is a set of interconnected neurons, which are organized in layers and which communicate only with the neurons to which it is connected. Characteristics of each neuron (i.e., the weights associated to each connection) are computed during the training phase.

[6] To train and validate our MLP, we used independent subsets of a large database of aerosol reflectances, $\rho_A(\lambda)$ at $\lambda = 670, 765$ and 865 nm computed using the radiative

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transfer model of *Chomko and Gordon* [1998] for various values of both $\tau(865)$ and $\alpha(510)$. These simulations depending also on the geometry of the measurement (i.e., the sun and viewing zenith angles, θ_S and θ_V , and the difference in azimuth angle, $\Delta\phi$, $\rho_A(\lambda)$ was computed for ten values of $\tau(865)$ between 0.05 and 0.8, for six values of $\alpha(510)$ between 0.2 and 2.2, for 21 values of both θ_S and θ_V (from 0° to 60° by step of 3°), and for 11 values of $\Delta\phi$ (from 0° to 360° by step of 36°). The variation of the Angström exponent within radiative transfer simulations was obtained by considering six weakly absorbing aerosol models characterized by a constant complex refractive index of $1.33 - i 0.0001$ and by a Junge power-law size distribution, whose size parameter ν varies from 2 to 4.5 by step of 0.5 [*Chomko and Gordon*, 1998]. A training database of 100,000 $\rho_A(\lambda)$ was randomly extracted out of these 360,000 simulations to optimize the architecture of the two MLP used here: The MLP for $\alpha(510)$ retrieval has two hidden layers with 10 neurons on the first and 6 on the second layer, while the one for $\tau(865)$ retrieval has 30 neurons on the first hidden layer and 15 on the second.

[7] We processed SeaWiFS orbits over the Mediterranean for the whole year 2000. We modified the SeaWiFS standard processing code to extract $\rho_A(\lambda)$ for each band as well as the complete geometry (θ_S , θ_V and $\Delta\phi$) for all clear-sky pixels of an orbit [*Moulin et al.*, 2001]. The cloud rejection test was also modified to avoid high aerosol optical thickness removal [*Moulin et al.*, 2001]. This processing code was used to mask the sun glint, correct ozone and water vapor absorptions, and subtract the whitecaps and Rayleigh scattering contributions, forming $\rho_A(\lambda)$. The complete geometry (θ_S , θ_V and $\Delta\phi$) and $\rho_A(\lambda)$ for each band are then entered into both MLP to get $\tau(865)$ and $\alpha(510)$.

3. Results

[8] Figure 1 shows maps of monthly means of $\tau(865)$ and $\alpha(510)$ for the central month of each season (January, April, July and October 2000). The seasonal cycle of $\tau(865)$ is dominated by the transport of mineral dust, which is characterized by frequent dust plumes extending over the central and eastern basins during spring and over the western basin during summer [*Moulin et al.*, 1998]. This influence is stronger in the southern part of the basin, where $\tau(865)$ reaches values as high as 0.35 in monthly mean near the Algerian and Libyan coasts. The Angström exponent of mineral dust is low and generally between 0.5 and 0.8. A strong North-South gradient is shown in Figure 1 on both $\tau(865)$ and $\alpha(510)$ maps during spring and summer. In contrast with the southern basin, which is influenced by mineral dust transport, the northern Mediterranean is characterized by relatively low $\tau(865)$ and high $\alpha(510)$ between 1 and 1.5. This suggests that aerosols in this region originate primarily from polluted regions of Europe [*Sciare et al.*, 2003]. The optical thickness is much lower over the whole Mediterranean during fall and winter, even if some transports of mineral dust occur in the central basin and along the Syrian coast during October [*Moulin et al.*, 1998]. The aerosols during this period are mostly of European origin as seen by the high monthly mean $\alpha(510)$ values of 1 to 1.5.

[9] Direct estimates of both $\tau(865)$ and $\alpha(510)$ performed at coastal Mediterranean stations within the framework of AERONET [*Holben*, 1998] were used to validate our neural

Figure 1. Monthly mean values of $\tau(865)$ (left panels) and $\alpha(510)$ (right panels) for January, April, July and October 2000.

network inversion. Hourly level 2.0 (cloud-screened and quality-assured) sun photometer measurements at three Mediterranean stations (Lampedusa, $35^\circ31'N-12^\circ37'E$; Oristano, $39^\circ54'N-08^\circ30'E$; Erdemli, $36^\circ33'N-34^\circ15'E$) stations were available for 2000. A fourth station, El Arenosillo ($37^\circ06'N, 6^\circ43'W$), was rejected because the instrument experienced calibration problems in the NIR (V. Cachorro, personal communication, 2003). Because sun photometers do not have a channel at 510 nm, $\tau(510)$, which is used to compute $\alpha(510)$, was linearly interpolated between $\tau(440)$ and $\tau(670)$ to ensure compatibility with both SeaWiFS estimates. A few apparent outliers still remain in the level 2.0 data and we decided to further remove measurements when $\alpha(510)$ is below zero or when $\tau(865)$ is below 0.05. The comparison of sun photometer measurements with satellite retrievals was made by extracting $\tau(865)$ and $\alpha(510)$ computed from both the standard and the MLP algorithms over the closest 3-by-3 pixel marine area distant of at least 5 km from the coast to avoid any turbid water contamination. We ended up with a set of 212 coincident measurements for MLP retrievals and only 157 for standard retrievals because of the more strict cloud mask.

[10] Figure 2 shows that the values of $\tau(865)$ retrieved using both MLP and standard inversions compare well with the optical thickness directly measured by the AERONET sun photometers. The correlation coefficient is higher for $\tau(865)$ retrieved with the MLP, whereas the standard algorithm leads to slightly less biased results. However, the most important result in Figure 2 is that the MLP inversion is capable of retrieving high optical thicknesses (i.e., greater than 0.35) with a good accuracy. In Figure 3, the Angström exponent retrieved with both methods is compared to that computed from sun photometer measurements. Even if $\alpha(510)$ retrieved with the MLP is underestimated by about

20%, it is shown to be much more accurate than that retrieved using the standard method, which is generally too low by a factor of two. This underestimation observed for both methods likely comes partly from the fact that aerosol absorption is not accounted for in radiative transfer simulations. Aerosol absorption does not affect much SeaWiFS measurements above 670 nm [Moulin *et al.*, 2001] but it impacts AERONET measurements at 443 nm and thus modifies the Angström exponent. Figure 3 also demonstrates the importance of considering aerosol models which cover a wide range of Angström exponent between 0 and 2, at least over oceanic region with significant continental influence, such as the Mediterranean. These comparisons between AERONET and SeaWiFS aerosol parameters show the benefit of our inversion technique based on neural networks.

4. Conclusion

[11] A new inversion technique based on Multi-Layered Perceptrons has been developed to retrieve aerosol optical thickness, $\tau(865)$, and Angström exponent, $\alpha(510)$, from SeaWiFS imagery. Two neural networks, one for each parameter, have been built and calibrated using a set of theoretical radiative transfer simulations performed using various aerosol optical properties. In order to account for a realistic range of $\alpha(510)$ between 0.2 and 2.2, we used a set of six Junge's power-law size distributions. SeaWiFS data were processed for year 2000 over the Mediterranean and the results were validated using AERONET measurements. This comparison shows that $\alpha(510)$ and $\tau(865)$ from the MLP inversion are retrieved with a good accuracy, even for high optical thicknesses up to 0.8, and are less biased than

Figure 2. Comparison of $\tau(865)$ retrieved from MLP ($\blacktriangle$) and standard ($\circ$) inversion methods with $\tau(865)$ measured at the three considered AERONET stations (see text). The regression line for our MLP inversion (solid line) has a slope of 1.12 and the correlation coefficient is 0.90 for 212 coincident measurements. The slope is unchanged and the correlation coefficient drops down to 0.82 if measurements with $\tau(865) > 0.35$ are excluded for compatibility with standard SeaWiFS products. For these latter products (dashed line), the slope is 1.04 and the correlation coefficient is 0.67 for 157 coincident measurements.

Figure 3. Comparison of $\alpha(510)$ retrieved from MLP ($\blacktriangle$) and standard ($\circ$) inversion methods with $\alpha(510)$ measured at the three considered AERONET stations (see text). The regression line for our MLP inversion (solid line) has a slope of 0.82 and the correlation coefficient is 0.68 for 212 coincident measurements. For the standard SeaWiFS product (dashed line), the slope is 0.5 and the correlation coefficient is 0.62 for 157 coincident measurements.

those from the standard processing. The method presented here is thus accurate and fast enough to process the whole SeaWiFS archive in order to facilitate the long-term monitoring of aerosol optical properties.

[12] **Acknowledgments.** The authors are grateful for support from the European project NAOC (Neural Algorithm for Ocean Color) and the firm ACRIST. We would like to thank M. Crépon for helpful comments, H. R. Gordon and R. Chomko for providing the synthetical database and Dr. Pugnaghi S., PI of Lampedusa AERONET station, Dr. Tanré, PI of Oristano AERONET station, Dr. Holben, PI of Erdemli AERONET and Dr. Cachorro of El Arenosillo AERONET station for maintaining and collecting the ground-based data. We also wish to thank the NASA Goddard Space Flight Center DAAC for providing all of the SeaWiFS data used in this study.

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