

Atmospheric correction of ocean color imagery through thick layers of Saharan dust

C. Moulin,¹

Laboratoire des Sciences du Climat et de l'Environnement, CEA-CNRS, Gif-Sur-Yvette, France

H.R. Gordon, R.M. Chomko

Department of Physics, University of Miami, Coral Gables, FL

V.F. Banzon,¹ R.H. Evans

Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL

Abstract. Airborne plumes of desert dust from North Africa are observable all year on satellite images over the Tropical Atlantic. In addition to its radiative impact, it has been suggested that this mineral dust has a substantial influence on the marine productivity. This effect is however difficult to gauge because present atmospheric correction algorithms for ocean color sensors are not capable of handling absorbing mineral dust. We apply a new approach to atmospheric correction in which the atmosphere is removed and the case 1 water properties are derived simultaneously. Analysis of SeaWiFS images acquired off Western Africa during a dust storm demonstrates the efficacy of this approach in terms of increased coverage and more reliable pigment retrievals.

Introduction

Phytoplankton, the first link in the marine food chain, can be detected from above the sea surface through the change in water color brought about by virtue of the photosynthetic pigment chlorophyll *a* and various accessory pigments they contain that absorb strongly in the blue portion of the spectrum. The seminal Coastal Zone Color Scanner (CZCS) mission demonstrated that these color variations could be measured from satellite altitudes [Gordon *et al.*, 1980] and led to the launching of several new ocean color sensors, the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), the Moderate resolution Imaging Spectroradiometer (MODIS), the POLarization and Directionality of Earth Reflectance (POLDER), etc.

Of the radiance measured by an in-orbit ocean color sensor (L_t) only a small portion (L_w) exited the ocean, typically $< 10\%$ in the blue, even less at longer wavelengths, and negligible in the near infrared (NIR). The rest is radiance backscattered from the atmosphere and reflected by the sea surface. This radiance must be removed from L_t (atmospheric correction) in order to retrieve L_w , the only part that contains information regarding marine productivity.

The principal difficulty in retrieving L_w lies in removing the effects of aerosols.

Assessment of the aerosol is now effected in a similar manner for all present ocean color sensors (e.g., Gordon and Wang [1994] for SeaWiFS). Aerosol is detected in two NIR bands and the observed spectral variation is compared to that of a set of aerosol models. The most appropriate are then used to remove the aerosol's contribution from L_t in the visible. Such algorithms are presently being successfully applied, except when the aerosol is strongly absorbing, because the aerosol's absorption is not detectable from the observed spectral variation in the NIR [Gordon, 1997]. Standard atmospheric correction in the presence of absorbing particles underestimates L_w in the blue leading to too-high pigment concentrations.

The predominant absorbing aerosol in the marine atmosphere is mineral dust coming from the Sahara [Herman *et al.*, 1997]. This dust is strongly absorbing in the blue because it contains ferrous minerals [Patterson, 1981]. In addition, the impact of this absorption is very dependent on the vertical distribution of the aerosol [Gordon, 1997]. This is of primary importance for Saharan dust. Because of these difficulties, the present algorithms do not process pixels when high L_t are detected in the NIR. The quasi-permanent presence of dust degrades satellite ocean color products in the Tropical Atlantic where large areas are not sampled, sometimes for as long as an entire month. This failure of the atmospheric correction also prevents observation of the potential fertilization effect due to the supply of nutrients contained in dust to the surface water [Young *et al.*, 1991].

Retrieval Algorithm

Our approach to atmospheric correction in the dust zone is the spectral matching algorithm (SMA) proposed by Gordon *et al.* [1997]. Briefly, a set of N candidate aerosol models is used along with a model of the water-leaving radiance as a function of the pigment concentration C and a marine particle-scattering parameter b^0 [Gordon *et al.*, 1988]. In this context, an aerosol model is comprised of a particle size distribution and index of refraction, with the radiative properties computed using Mie theory, and a vertical distribution of aerosol concentration. C is defined to be the sum of the concentrations of chlorophyll *a* and its degrada-

¹Also at Physics Department, University of Miami, Coral Gables, FL 33124

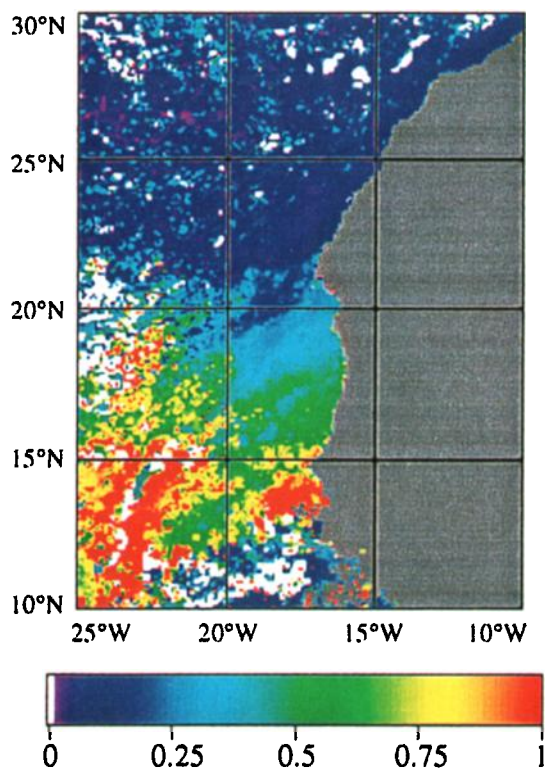


Figure 1. 8-day mean (30 Sept. – 7 Oct., 1997) of the AOD as retrieved using the SMA.

tion product phaeophytin *a*. It is the bio-optical quantity that was estimated by the CZCS. The *Gordon et al.* [1988] radiance model was tuned to *C* using in-situ measurements in case 1 waters in the Eastern Pacific, Gulf of California, Western Atlantic, and Gulf of Mexico.

The aerosol optical depth at 865 nm (AOD) for each aerosol model is adjusted so that the computed top of the atmosphere (TOA) radiance exactly reproduces the measured value in the NIR. This allows the contribution of the atmosphere to the TOA radiance to be computed throughout the visible for each aerosol model. The marine contribution for a given *C* and b^0 is then added to the atmospheric contribution for each of the *N* models to provide the modeled TOA radiance throughout the visible. For each aerosol model, we then systematically varied *C* (17 values, from 0.03 to 3 mg/m^3) and b^0 (12 values, from 0.12 to 0.45) over the range characteristic of case 1 waters to obtain the best agreement, in a root-mean square (RMS) sense, between the modeled and measured TOA spectral radiances.

Realistic aerosol models are crucial for obtaining accurate estimates for the ocean properties using this approach. We developed a set of mineral dust models based on earlier work with Meteosat [*Moulin et al.*, 1997]. Comparisons between in-situ and Meteosat-retrieved AOD showed that the *Shettle* [1984] “Background Desert” model was superior to a wide range of other models. The real part of the aerosol’s refractive index was set to 1.53 and its imaginary part was set after *Patterson* [1981]. This provided the basic model from which a set of 18 candidate dust models was developed by using three contributions of the coarse mode to the size distribution, two spectral variations of the absorption index (*Patterson*’s and a lower limit set by examination of several

SeaWiFS images), and three thicknesses of the dust layer (*C. Moulin, H. Gordon, R. Evans, and V. Banzon, unpublished, 1999*).

We applied the SMA to SeaWiFS on a pixel-by-pixel basis. Since the cloud screening of the standard algorithm removed most of the bright “dusty” pixels, we decided to replace it by a threshold on the standard deviation of the TOA radiance at 865 nm computed on 3×3 pixels [*Moulin et al.*, 1997]. This threshold was set by trial and error to 0.5 $\text{mW}/\text{cm}^2\mu\text{mSr}$ using imagery from the area of interest. It produces a more conservative, and we believe better, cloud screen than that of the standard algorithm, although it may pass marine stratus as dust. For the non-cloudy pixels that were then processed using the SMA, we do not report the retrieved pigment concentration when the retrieved AOD is greater than 0.8. This prevents misidentification of marine stratus.

A unique feature of SeaWiFS is the bilinear radiometric response so there is high sensitivity for dark targets (ocean) and low sensitivity for bright targets (clouds) [*Hooker, et*

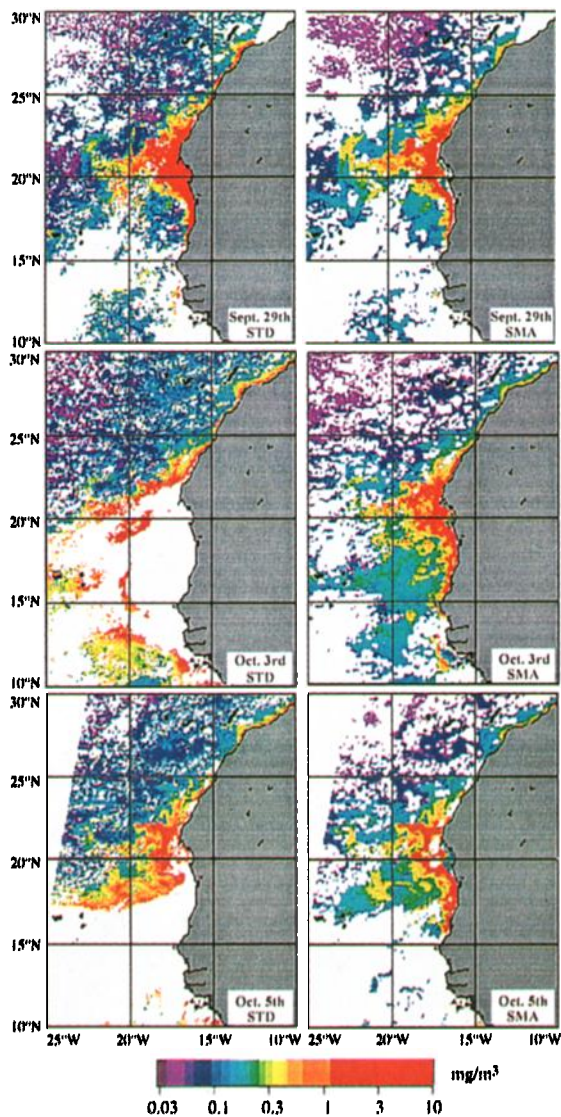


Figure 2. Pigment concentrations for a clear day and two “dusty” days using the STD and the SMA processings.

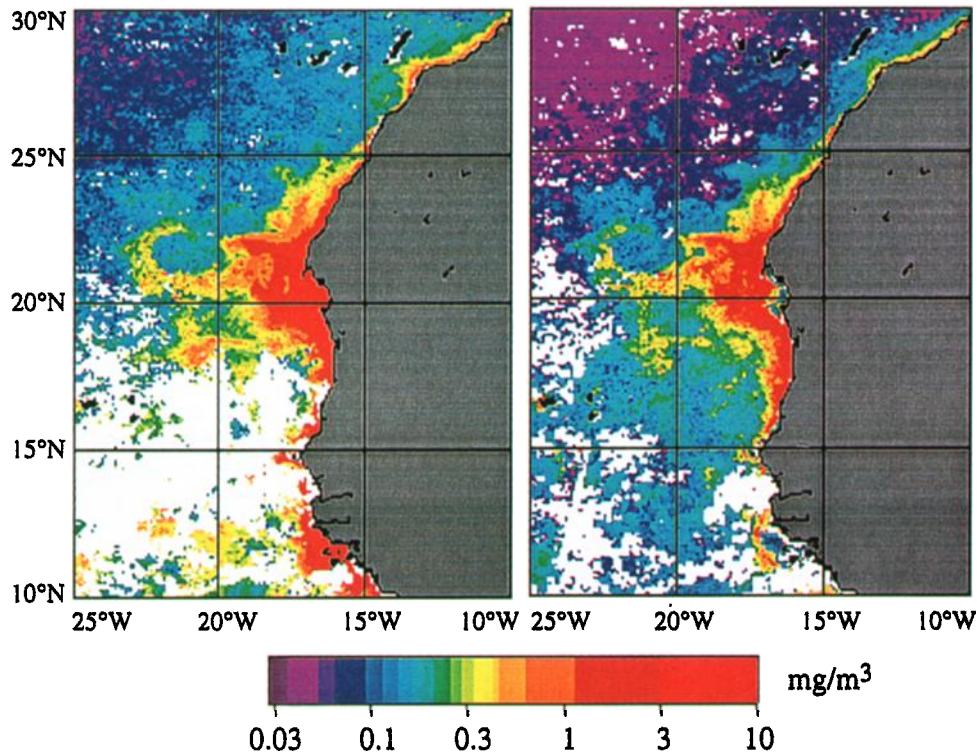


Figure 3. 8-day means (30 Sept. – 7 Oct., 1997) of the pigment concentration using STD (left) and SMA (right) processings.

al., 1992]. In dust plumes, the NIR radiance is usually in the upper (less sensitive) part of the gain curve when the AOD is $>$ about 0.5, while the visible radiances are in the lower (more sensitive) part of the gain curve for AOD $<$ about 1. Thus restricting the pigment reporting to AOD $<$ 0.8 reduces the degradation of the quality of the retrievals by virtually assuring that the visible bands are all acquired in the more sensitive region.

Sample Results

We applied the SMA along with the University of Miami implementation of the standard SeaWiFS algorithm to an 8-day period acquired off the West Coast of Africa between September 30 and October 7, 1997. This time period was chosen because it enables comparison with the standard SeaWiFS 8-day product. During this period, 5 SeaWiFS orbits (October 1, 3, 4, 5 and 7) crossed our region of interest (10° – 30° N; 10° – 25° W). An intense dust event, shown in Figure 1, is observable between 10° N and 20° N on all orbits during this period, obscuring the signal from the sea surface. The most interesting region to test our improved atmospheric correction is between 15° N and 20° N, where the mean AOD ranges mainly from 0.2 to 0.8, as we expect the standard atmospheric correction to be degraded even for relatively low AOD. North of the dust zone, between 20° N and 30° N, AOD remains low (≤ 0.1) during the period.

Figure 2 provides a comparison of the retrieved pigment concentrations from the SMA and the standard SeaWiFS (STD) chlorophyll product of single orbit retrievals for the nearest “non-dusty” day (September 29) outside of the dust event. During this clear day, the AOD was about 0.1 over the whole region, so that the retrieved pigment concentra-

tions can be used as a reference to describe the actual marine productivity of this entire region. The STD chlorophyll product uses the algorithms of *Gordon and Wang* [1994] for atmospheric correction and of *O’Reilly et al.* [1998] (OC2) for retrieving the chlorophyll concentration from L_w . In contrast to the *Gordon et al.* [1988] model that was tuned to pigment concentration, the *O’Reilly et al.* [1998] algorithm is an empirical fit to chlorophyll a . C is approximately 35% greater than the concentration of chlorophyll a [*O’Reilly et al.*, 1998]; however, for the same water-leaving radiances the *Gordon et al.* [1988] pigment concentration and the *O’Reilly et al.* [1998] chlorophyll a can differ as much as a factor of two, with C even lower than chlorophyll a over some of the range. Rather than trying to reconcile the existing differences between these two bio-optical algorithms, we decided that for atmospheric correction purposes it is sufficient to compare the pigment concentration from the SMA to the chlorophyll a concentration from the STD processing.

At the regional scale, it is obvious that both algorithms lead to very similar results for oligotrophic waters as well as for the very productive Mauritanian upwelling. Indeed, even though the aerosol models used to perform the atmospheric correction are completely different (i.e., weakly- or non-absorbing for STD and absorbing for SMA), the aerosol contribution to the TOA radiance is small enough so that it does not significantly influence the pigment retrievals. A more detailed analysis however reveals some discrepancies between the two results that are likely due to the difference in the derived product (chlorophyll a for STD and pigment for SMA), as well as the bio-optical models used to estimate the pigment concentration from L_w . For instance, there is an overestimate of the pigment concentration compared to chlorophyll a in areas between 25° W and 23° W at about

20°N, and between 19°W and 16°W at about 17°N. In the case 2 waters along the African coast at about 20°N, the SMA retrieves very low pigment concentrations because it is based on the case 1 water model of Gordon *et al.* [1988]. Also, one should note that the maximum pigment concentration that can be reached within our SMA for case 1 waters is 3 mg/m³, whereas the O'Reilly *et al.* [1998] empirical algorithm is designed to retrieve chlorophyll *a* concentrations as high as 30 mg/m³. Despite these differences, the general agreement between the two results is satisfactory for this dust-free image.

Figure 2 also shows single orbit retrievals of the pigment concentration for two "dusty" days (October 3 and 5). Contrary to what was shown for the clear day, the two algorithms lead to very different results. The continuity of the SMA algorithm between the two dusty days and the clear day suggests that it has been successful in removing much of the influence of the dust from the October 3 and 5 images. In contrast, the standard algorithm shows very high chlorophyll concentrations in the edge of the dust plume, but it retrieves reasonable concentrations away from the plume, although comparison with the clear day shows that the STD algorithm returns higher values north of 25°N. This cannot be due to a difference of bio-optical algorithm, but rather to low concentrations of dust. In contrast, the SMA retrieves essentially the same pigment concentration in this region on all three days.

We computed the corresponding concentration means of non-cloudy pixels for the 8-day period from September 30 to October 7. Both the SMA pigment and the SeaWiFS standard chlorophyll *a* product (acquired from the NASA/GSFC web site) are shown on Figure 3. It is evident that the SMA yields significantly more coverage in the dust region between 13°N and 18°N. Furthermore, in the region between 10°N and 13°N, the STD algorithm actually processes the imagery, but yields concentrations that are much too high (compare Figure 3 with Figure 2 for the clear day). Above 25°N, the STD concentrations are also slightly too high, presumably because of a background of dust. In contrast, over most of the area studied, the SMA retrieves approximately the same pigment concentrations over the eight days as it did in the absence of dust. This suggests that the SMA provides significantly better pigment retrievals and spatial coverage than the STD does in producing the standard SeaWiFS chlorophyll product.

Concluding Remarks

We have applied an algorithm, developed for atmospheric correction of ocean color imagery in strongly absorbing atmospheres, to SeaWiFS imagery acquired in the region of Saharan dust transport off the coast of Africa. Application required a set of candidate aerosol models, developed by studying SeaWiFS imagery in intense dust storms in the same region. The results indicate that the methodology shows considerable promise for processing ocean color imagery in the presence of mineral dust, and immediately suggests the possibility of estimating other important consequences of the presence of dust, e.g., short-wave radiative forcing, radiative heating and its vertical distribution in the troposphere, etc. The methodology, i.e., developing and tuning candidate aerosol models using SeaWiFS imagery, can be applied to other regions and to other ocean color sensors in the same straightforward manner. The present dust mod-

els permit processing close to the African coast. The models need to be validated, or new models developed, for regions in the dust zone farther off shore, as significant changes in the size distribution and particle characteristics may occur as the dust progresses across the Atlantic.

Acknowledgments. The authors are grateful for support for this work under the following grants and contracts: NASA NAS5-31363 (HRG, CM), NASA NAS5-31734 (HRG, VFB), NASA NAS5-31362 (RHE). We also wish to thank the NASA/GSFC DAAC for providing all of the SeaWiFS data used in this study. This is contribution 0515 from LSCE.

References

- Gordon, H.R., D.K. Clark, J.L. Mueller, and W.A. Hovis, Phytoplankton pigments derived from the Nimbus-7 CZCS: Initial comparisons with surface measurements, *Science*, *210*, 63-66, 1980.
- Gordon, H.R., O.B. Brown, R.E. Evans, J.W. Brown, R.C. Smith, K.S. Baker, and D.K. Clark, A Semi-Analytic Radiance Model of Ocean Color, *J. Geophys. Res.*, *93D*, 10909-10924, 1988.
- Gordon, H.R., and M. Wang, Retrieval of water-leaving radiance and aerosol optical thickness over the oceans with SeaWiFS: A preliminary algorithm, *Applied Optics*, *33*, 443-452, 1994.
- Gordon, H.R., Atmospheric Correction of Ocean Color Imagery in the Earth Observing System Era, *J. Geophys. Res.*, *102D*, 17081-17106, 1997.
- Gordon, H.R., T. Du, and T. Zhang, Remote sensing ocean color and aerosol properties: Resolving the issue of aerosol absorption, *Applied Optics*, *36*, 8670-8684, 1997.
- Herman, J.R., P.K. Bhartia, O. Torres, C. Hsu, C. Seftor, and E. Celarier, Global distributions of UV-absorbing aerosols from Nimbus 7/TOMS data, *J. Geophys. Res.*, *102D*, 16889-16909, 1997.
- Hooker, S.B., W.E. Esaias, G.C. Feldman, W.W. Gregg, C.R. McClain, An Overview of SeaWiFS and Ocean Color, *SeaWiFS Technical Report Series: Volume 1, NASA Technical Memorandum 104566*, Eds. S.B. Hooker and E.R. Firestone, Greenbelt, MD, July 1992.
- Moulin, C., F. Dulac, C.E. Lambert, P. Chazette, I. Jankowiak, B. Chatenet, and F. Lavenu, Long-term daily monitoring of Saharan dust load over ocean using Meteosat ISCCP-B2 data, 2, Accuracy of the method and validation using sunphotometer measurements., *J. Geophys. Res.*, *102D*, 16959-16969, 1997.
- O'Reilly, J.E., S. Maritorena, B.G. Mitchell, D.A. Siegel, K.L. Carder, S.A. Garver, M. Kahru, C. McClain, Ocean color chlorophyll algorithms for SeaWiFS, *J. Geophys. Res.*, *103C*, 24937-24953, 1998.
- Patterson, E.M., Optical Properties of Crustal Aerosol: Relation to Chemical and Physical Characteristics, *J. Geophys. Res.*, *86C*, 3236-3246, 1981.
- Shettle, E. P. Optical and radiative properties of a desert aerosol model, in *Proc. Symposium on Radiation in the Atmosphere*, edited by G. Fiocco, pp. 74-77, A. Deepak, Hampton, VA, 1984.
- Young, R.W., K.L. Carder, P.R. Betzer, D.K. Costello, R.A. Duce, G.R. Ditullio, N.W. Tindale, E.A. Laws, M. Uematsu, J.T. Merrill, and R.A. Feeley, Atmospheric Iron Inputs and Primary Productivity: Phytoplankton Responses in the North Pacific, *Global Biogeochem. Cycles*, *5*, 119-134, 1991.

V. Banzon, R. Evans, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL 33149. (e-mail: viva@rrsl.rsmas.miami.edu; bob@rrsl.rsmas.miami.edu)

R. Chomko, H. Gordon, Department of Physics, University of Miami, Coral Gables, FL 33124. (e-mail: chomko@physics.miami.edu; hgordon@miami.edu)

C. Moulin, Laboratoire des Sciences du Climat et de l'Environnement, CEA-CNRS, 91191 Gif-Sur-Yvette, France. (e-mail: cyril.moulin@cea.fr)

(Received June 19, 2000; accepted October 18, 2000.)