Pitfalls in atmospheric correction of ocean color imagery: how should aerosol optical properties be computed?: reply to comment

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Gordon [Appl. Opt. **42,** 542 (2003)] argues that use of external rather than internal mixing when aerosol optical properties are computed will not seriously affect atmospheric correction of ocean color imagery, in spite of the fact that top of the atmosphere reflectances computed with the two approaches differ significantly as shown by Yan *et al.* [Appl. Opt. **41**, 412 (2002)]. We apply an algorithm for simultaneous retrieval of aerosol optical properties and chlorophyll concentrations to demonstrate that use of the internal-mixing approach leads to atmospheric corrections that differ significantly from those obtained with the more realistic external-mixing approach. For relative humidities of 90% or more, the differences in retrieved aerosol optical properties and chlorophyll concentrations, incurred by application of the internal-mixing approach, become unacceptably large.

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Gordon[1] makes one essential point: He disagrees with the conclusions reached by Yan *et al.*[2] The main point of the paper by Yan *et al.* is to show that computed optical properties of atmospheric aerosols depend sensitively on the assumptions made about how a mixture of aerosols with different chemical compositions and hygroscopicities grow and change their refractive indices with increasing humidity.

Shettle and Fenn[3] introduced a set of basic aerosol models. Four of these models have been used extensively for atmospheric correction of ocean color imagery. These are the tropospheric, coastal, maritime, and urban aerosol models, each consisting of a multicomponent (MC) mixture of dry aerosol particles that will grow when exposed to a humid environment. To compute the optical properties associated with these aerosol models, assumptions must be made concerning how these dry aerosol particles grow and mix when exposed to enhanced humidity. The purpose of the paper by Yan *et al.*[2] was to investigate the consequence of two different assumptions invoked to compute the aerosol optical properties of a MC mixture of atmospheric aerosols. The tropospheric and urban models were used for demonstration purposes as examples of a weakly and a strongly absorbing aerosol type, respectively, as defined by Shettle and Fenn.[3] Yan *et al.*[2] compared two approaches for computing the optical properties of a mixture of aerosols consisting of several different components. One of these is the single-component (SC) approach based on the internal-mixing rule adopted by Shettle and Fenn.[3] This SC approach has been widely applied to atmospheric correction of ocean color imagery including that obtained by the Sea-Viewing Wide Field-of-View Sensor (Sea WiFS) sensor. The other method investigated by Yan *et al.* is the MC or external-mixing approach.[4] Yan *et al.* compared the aerosol optical properties computed using the SC and MC approaches and the simulated top of the atmosphere (TOA) reflectances resulting from using these two different optical properties. On the basis of this comparison, Yan *et al.* concluded that it is important to treat light scattering by aerosols correctly to obtain accurate and reliable atmospheric correction, because the MC approach, which is believed to be more realistic, yields results that are significantly different from those of the SC approach. Although the MC

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approach is more realistic than the SC approach, Yan *et al.* suggested that a closure experiment be conducted to test the validity of the MC approach in view of its limitations.

Yan et al. did not investigate whether the aerosol models defined by Shettle and Fenn[3] are realistic and sufficient for the task of atmospheric correction of ocean color imagery produced by the present-generation sensors, but suggested that this is an important issue that merits consideration. The purpose of the Yan *et al.* paper was exclusively to investigate if the internal-mixing method is adequate for computing the aerosol optical properties for the aerosol models defined by Shettle and Fenn.[3] Thus the purpose was not to investigate the realism of the aerosol models defined by Shettle and Fenn or to criticize their use in current atmospheric correction efforts, but rather to show that, for the Shettle and Fenn aerosol models, the MC approach (external mixing) yields results that are significantly different from those of the SC approach (internal mixing).

Gordon[1] states that the aerosol optical properties computed with the SC approach are (i) sufficiently accurate for the SeaWiFS ocean color imagery task and (ii) realistic enough for the task of atmospheric correction of most ocean color imagery produced by the present-generation sensors. In support of these claims, Gordon[1] refers to results provided primarily in four papers.[5–8]

In Ref. 5 the calibration and validation of SeaWiFS data were investigated. In Fig. 4 of Ref. 5, a comparison is displayed between chlorophyll-α concentration values derived from *in situ* match-up data and satellite retrievals. From this figure, it is clear that the uncertainty of the data at low (less than 0.3 mg m^{-3}) and high (greater than 3 mg m^{-3}) chlorophyll-α concentrations is not usually within $\pm 35\%$. The upper left panel in Fig. 5 of Ref. 5 shows large discrepancies between water-leaving radiances at visible wavelengths obtained from SeaWiFS retrievals and *in situ* measurements. Some of these discrepancies are much larger than $\pm 5\%$. There are also some negative water-leaving radiances retrieved by the SeaWiFS algorithm. Thus Ref. 5 merely shows that the current SeaWiFS atmospheric correction algorithm may work well in some regions of case 1 waters.

In Ref. 7 it is pointed out (by citing Ref. 6) that the aerosol optical thickness can usually be retrieved to within an uncertainty of $\sim 10\%$ (or $\sim 0.01–0.02$) by the SeaWiFS algorithm. In Ref. 6 this conclusion is based on a test involving three aerosol models [maritime, coastal, and tropospheric aerosol models at a relative humidity (RH) of 80%] when the aerosol optical depth at 865 nm is 0.2 or 0.4. Because this test involves a limited number of aerosol models and aerosol optical depths, it is difficult to reach a general conclusion. Reference 8 provides SeaWiFS aerosol optical thickness match-up analyses. Figures 26a–26d in Ref. 8 show that a discrepancy larger than $\pm 10\%$ is present in many cases between the aerosol optical depth retrieved from SeaWiFS data and that retrieved from ground-based CIMEL sun-sky radiometer data. This discrepancy is large enough to cause a nonnegligible error in ocean color retrieval. References 7 and 8 provide insufficient evidence that the SeaWiFS algorithm yields reasonably good estimates of the aerosol optical depth at 865 nm.

Thus Gordon[1] only shows that the current SeaWiFS algorithm, which employs the aerosol optical properties computed by the SC approach from the Shettle and Fenn aerosol models, works to some extent (but not for most regions of case 1 waters) for the task of atmospheric correction of ocean color imagery produced by present-generation sensors.

Gordon[1] disagrees that Yan *et al.*[2] have uncovered a pitfall in atmospheric correction because he claims that Yan *et al.* did not demonstrate that the MC approach will yield a better atmospheric correction through direct application to ocean color imagery. This is a valid concern that deserves serious consideration. It leads, however, to the question: How does one assess the validity of a scientific method? In principle, this can be done theoretically, experimentally, or through a combination of theory and experiment. In the laboratory the validity of a theoretical approach can be examined by carefully designed and executed controlled experiments. In nature such experiments are difficult to carry out in a controlled manner.

As discussed by Gordon,[1] atmospheric correction of ocean color imagery involves many steps: (i) the selection of candidate aerosol models, (ii) computation of aerosol optical properties for these candidate models, (iii) estimation of aerosol optical properties at near-infrared wavelengths, and (iv) removal of the atmospheric contribution at visible wavelengths. The last step is required to estimate the water-leaving radiance at visible wavelengths that is used in most existing methods to determine the chlorophyll concentration. This implies that the accuracy of the atmospheric correction is determined by uncertainties that exist in each of these four steps. It is clear, however, that the accuracy of the optical properties computed for the candidate aerosol models is a key factor needed to determine the accuracy of the atmospheric correction, and thus the accuracy of the ocean color retrieval.

Now we return to the important question: How do we decide whether the MC approach provides atmospheric correction that is significantly different from that of the SC approach? As explained above, this is difficult to do through direct application to ocean color imagery because it requires the application of a retrieval algorithm that introduces uncertainties related to the simulation of the entire retrieval process. We do not expect such an approach to be useful for deciding whether the MC approach provides retrievals that are significantly different from those of the SC approach because uncertainties related to the retrieval procedure could easily mask or reduce differences that are due to different treatments of the aerosol optical properties.

However, there is an alternative way to proceed.

We can use a new algorithm for simultaneous retrieval of aerosol optical properties and chlorophyll concentrations in case 1 waters.[9] This algorithm is based on a comprehensive discrete ordinate radiative transfer code for the coupled atmosphere–ocean system (CAO-DISORT) by use of a complete bio-optical model for case 1 waters.[10] Also, because the MC approach is believed to be more realistic than the SC approach, and hence should lead to a better representation of the TOA radiances than the SC approach, the new retrieval algorithm is based on aerosol optical properties computed by the MC approach. This CAO-DISORT radiative transfer code has been tested against a Monte Carlo method and shown to give accurate results.[11] It has also been tested against reflectance data in the SeaWiFS Bio-Optical Algorithm Mini-workshop (SeaBAM) database.[12] These tests show that the CAO-DISORT code produces realistic water-leaving radiances[9,10] for a large range of chlorophyll concentrations.

The new retrieval algorithm[9] is based on look-up tables established when the CAO-DISORT radiative transfer code is run for a variety of cases involving a wide range of different Sun-sensor geometries, 16 different aerosol models with optical properties computed by the MC approach for optical depth values ranging from 0.05 to 0.8, and for chlorophyll concentration values in the ocean ranging from 0.03 to 20 mg m^{-3}. The resulting look-up tables are then used in an iterative procedure for simultaneous retrieval of atmospheric aerosol properties and oceanic chlorophyll concentrations. Testing of the retrieval algorithm against synthetic data shows that it provides accurate results.[9]

We now apply the new retrieval algorithm to answer the important question: Does the MC approach provide a better atmospheric correction than the SC approach when applied to synthetic data? To address this question we tested the ability of the new algorithm to retrieve the aerosol model and the optical depth at 865 nm as well as the oceanic chlorophyll concentration. In the top panels of Fig. 1 we show the retrieved aerosol optical depth at 865 nm plotted against the input values used to generate the TOA radiances employed in the retrieval algorithm. The upper left panel pertains to synthetic radiances based on the SC approach, whereas the upper right panel pertains to synthetic radiances computed by the MC approach. The retrieved chlorophyll concentrations are shown in the lower panels of Fig. 1. This comparison is for a maritime aerosol model at 50% RH. As pointed out by Yan *et al.*,[2] the difference in the optical properties obtained with the SC and MC approach is relatively small at 50% RH. Nevertheless, we note that the retrieved chlorophyll concentrations obtained with the MC approach to generate synthetic data differ significantly from those obtained with the SC approach.

Figure 2 shows results obtained for the same situation as in Fig. 1 except that the RH is changed from 50% to 99%. We note that in this case use of the SC approach to generate synthetic TOA radiances leads

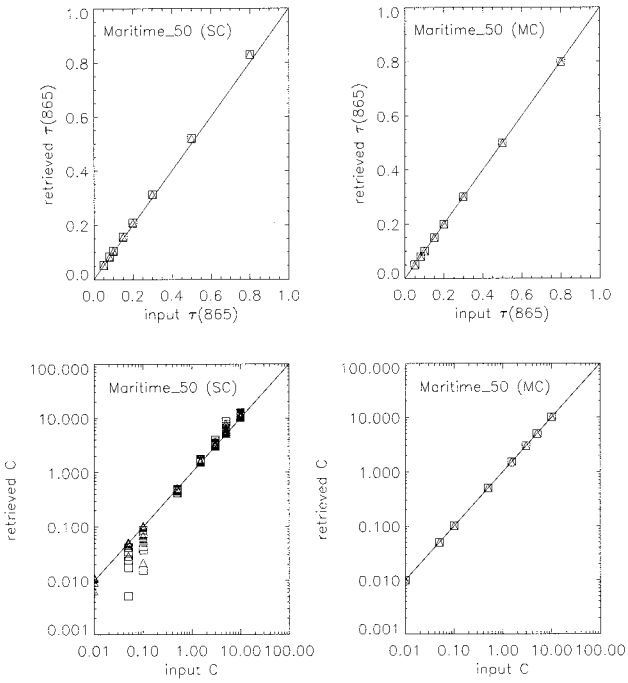

Fig. 1. Comparison of retrieved aerosol optical depths and chlorophyll concentrations with input data. The maritime aerosol model with 50% RH was used to compute aerosol optical properties. The left panels show results based on aerosol optical properties computed with the SC approach, whereas the right panels pertain to the MC approach. Triangles, Sun-sensor geometry: $\theta_0 = 54.4°$, $\theta = 25.60°$, $\Delta\phi = 56.0°$; squares, Sun-sensor geometry: $\theta_0 = 54.4°$, $\theta = 68.03$, $\Delta\phi = 56.0$.

to large discrepancies both in the retrieved aerosol optical depths and in the chlorophyll concentrations.

Figures 3 and 4 show results similar to those in Figs. 1 and 2, but now for the troposheric aerosol model. Figures 1 and 3 demonstrate that small discrepancies in the retrieved optical depths at 865 nm resulting from use of the SC approach instead of the MC approach to generate synthetic TOA radiances may lead to relatively large discrepancies in the retrieved chlorophyll concentrations even when the RH is as low as 50%. The reason is that the extrapolation from the near infrared into the visible leads to discrepancies in the aerosol contribution to the TOA radiance in the visible that are sufficiently large to give significant discrepancies in the retrieved water-leaving radiance. Thus, because the aerosol contribution to the TOA radiance is much larger than the contribution from the water-leaving radiance, a relatively small discrepancy in the former may lead to an unacceptably large discrepancy in the retrieved water-leaving radiance. It is clear from Figs. 2 and 4 that for large RH the discrepancies in the retrieved aerosol optical depths as well as in the chlorophyll concentrations become unacceptably large.

In summary, Yan *et al.*[2] showed that TOA reflectances computed with the MC approach differ from those obtained with the SC approach when the aerosol models defined by Shettle and Fenn[3] are

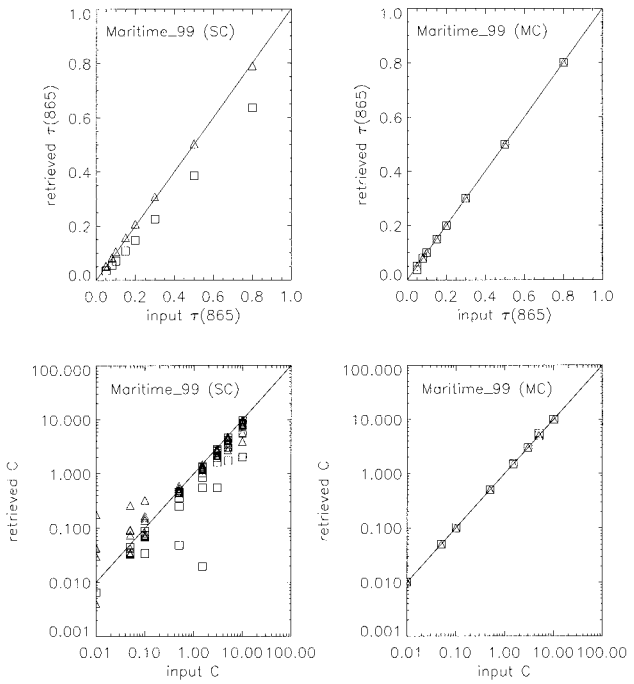

Fig. 2. Comparison of retrieved aerosol optical depths and chlorophyll concentrations with input data. Same as Fig. 1 except that the maritime aerosol model with 99% RH was used to compute aerosol optical properties.

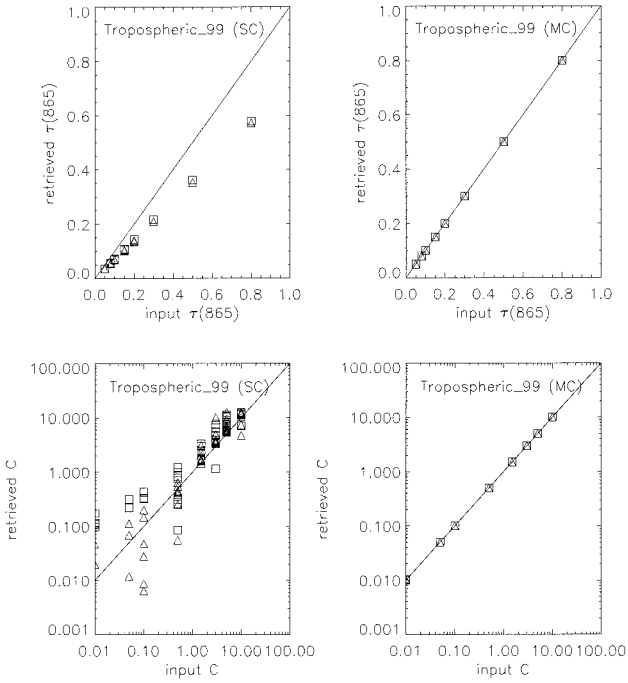

Fig. 4. Comparison of retrieved aerosol optical depths and chlorophyll concentrations with input data. Same as Fig. 1 except that the tropospheric aerosol model with 99% RH was used to compute aerosol optical properties.

adopted. They also showed that these two approaches could lead to TOA reflectance deviations that are larger than the TOA reflectance contributions from the water-leaving radiances. Here we have used an algorithm for simultaneous retrieval of aerosol optical properties and chlorophyll concentrations[9] to demonstrate that use of the SC approach to generate synthetic TOA radiances yields large discrepancies both for the retrieved aerosol optical properties and for the chlorophyll concentrations in case 1 waters. For RHs of 90% or more, these discrepancies become unacceptably large.

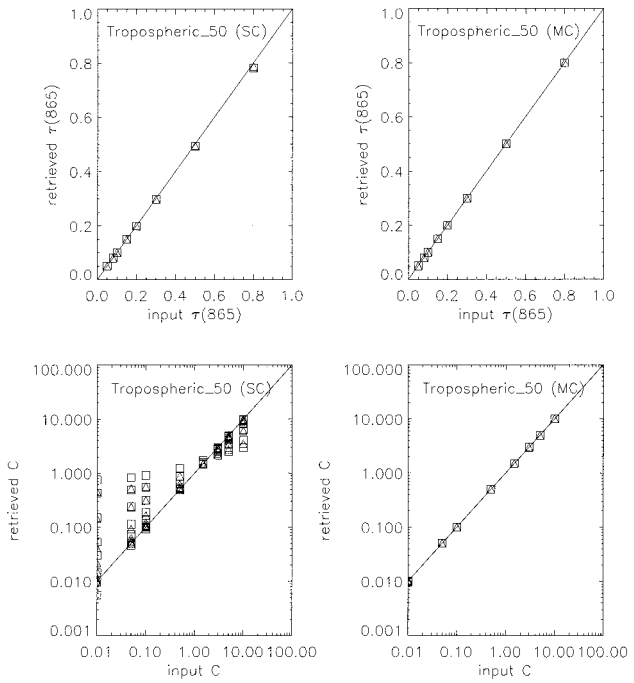

Fig. 3. Comparison of retrieved aerosol optical depths and chlorophyll concentrations with input data. Same as Fig. 1 except that the tropospheric aerosol model with 50% RH was used to compute aerosol optical properties.

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