Simulated Effects of Barometric Pressure and Ozone Content
Upon the Estimate of Marine Phytoplankton From Space

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Barometric pressure and total ozone content may significantly depart from their mean climatology values; these values, however, are used when processing the visible remote sensing (VRS) data with the aim of estimating the phytoplanktonic pigments concentration (chlorophyll $a +$ phaeophtyn $a$, in milligrams per cubic meter) within the upper ocean. The effect of ignoring such departures upon the retrieved concentration has been simulated for the broad oceanic range (0.015–20 mg/m$^3$). The simulation is effective for typical VRS situations (geometry, aerosol) when information about the variable aerosol is not available when entering the processing (as is the case with the Coastal Zone Color Scanner (CZCS) data) or, conversely, when such information has been separately obtained (simulation of future sensors with dedicated near-IR channels). The result is that in both these cases the use of mean climatology values leads to variable misestimates of the pigment content, by a factor of up to 2 in many common VRS situations, and above 2 for very low or high actual pigment content. After the results are discussed, the conclusion is that the actual values of the barometric pressure and of the ozone content will have to be introduced in the processing of future visible sensor data in order to preserve the expected accuracy. With regard to the exploitation of the CZCS archive, this requirement is not so essential, insofar as the pressure and ozone effects on the pigment concentration retrieval remain of the same order as the noise due to the limited radiometric accuracy of this sensor. However, at the scale of a CZCS scene, neglecting the strong structures in the pressure and ozone content fields may bias the phytoplankton concentration mapping. The use of the actual values is therefore recommended.

1. INTRODUCTION

At visible wavelengths both media in the ocean-atmosphere system passively contribute to radiances measured by an orbital downlooking sensor. The upper layer of the ocean backscatters skyward a small part of the incoming solar flux crossing the air-sea interface. This returning flux is strongly "colored," i.e., spectrally modified, by the water and its content in such a way that the "blue-to-green" ratio of ocean-leaving radiances can reliably be related to phytoplankton pigment concentration (chlorophyll $a +$ phaeophtyn $a$) through bi-optical algorithms [Clarke et al., 1970; Morel and Prieur, 1977]. At spacecraft level, however, the "marine signals" account at the most for 15% of the total signals $L$, in favorable cases [Clarke et al., 1970; Gordon, 1978]. Their retrieval then requires a highly precise evaluation of the atmospheric contribution to $L$, due to "Rayleigh" scattering by air molecules and "Mie" scattering by aerosol particles. This evaluation is known as the "atmospheric correction" step in the processing of oceanic visible remote sensing (VRS) data.

As far as VRS requires clear atmospheres, the assumption of single scattering [Gordon, 1978] is valid as a first approximation. Under this assumption the three contributions (aerosol, molecular, and oceanic) are simply additive, and separate descriptions are allowed.

The total number of gas molecules in the vertical column directly governs the Rayleigh fraction of the scattering and as far as the actual value of the atmospheric thickness (which is proportional to the ground pressure $p$) is used, this contribution is easily and accurately computed. As regards aerosol contribution, Mie computation techniques might be applied to any particle population the nature and size distribution of which is known (see, e.g., Quenzel and Kaestner [1980]), a condition difficult to meet in practice. In particular, processing the Coastal Zone Color Scanner (CZCS) data implies deriving the aerosol signals as well as the marine ones.

Beyond taking a hand in the scattering process, some of the atmospheric gases modify through absorption both the downwelling and upwelling light fluxes. In the visible range and over a weak absorption background by other minor constituents, ozone exhibits a broad absorption band ("Chapuis band") centered on 580–590 nm with a half bandwidth of 120 nm.

Climatologic mean values (seasonally varying and zonally averaged) for ground pressure and total ozone content are usual inputs in standard VRS processing (such as those developed for CZCS) despite the fact that these parameters, on daily scale and over a few hundred kilometers, may experience fluctuations higher than the seasonal variations. Pressure differences of more than 1% can be observed within the scene in sight of an orbital radiometer (it is acknowledged that low pressures, often accompanied by clouds, do not allow the capture of the ozone signal). With respect to ozone the total content exhibits a short time variability with high amplitude (up to $\pm 20\%$) superimposed on its annual cycle (see, e.g., Krueger et al. [1981] and Bowman and Krueger [1985]). Using standard rather than actual values for ground pressure may therefore lead to significant misestimates of the radiation scattered by molecules, especially at blue wavelengths, owing to the strong spectral selectivity of Rayleigh scattering. Assigning standard values to the ozone content may lead to erroneous values of the atmospheric absorption especially in the green part of the spectrum, where ozone is the most efficient. The present work is directed at exploring the consequences of such misestimates on the retrieval of the marine signals and particularly of the blue-to-green ratio on which rests the algal pigment retrieval. The aerosol effect, not considered per se, cannot, however, be ignored to the extent that it interacts with those effects examined here. The problem is first studied as a physical problem. The practical aspect is examined by com-
paring the expected effects with those resulting from technological limitations (radiometric sensitivity and digitization).

2. EXPRESSING THE SIGNALS

Assuming that multiple scattering is negligible and that the radiometer does not aim at the Sun glint, \( L_s \) may be written (same notation as used by Gordon and Morel [1983]):

\[
L_s(\lambda, \theta, \theta_o, \phi) = L_{\text{atm}}(\lambda, \theta, \theta_o, \phi) + L_w^*(\lambda, \theta, \theta_o) \tag{1}
\]

where \( L_{\text{atm}} \) is the atmospheric signal and \( L_w^* \) the marine signal at spacecraft level, \( \lambda \) is the wavelength, \( \theta \) is the zenith angle of sighting direction (pixel to spacecraft), \( \theta_o \) is the Sun zenith angle (pixel to Sun), and \( \phi \) is the azimuthal angle difference between the vertical planes containing the sensor and the Sun. Henceforth the angles \( \theta, \theta_o, \phi \) will be suppressed in the presentation of all the radiometric symbols.

Atmospheric Signal

\( L_{\text{atm}} \) in (1) is given by

\[
L_{\text{atm}}(\lambda) = T_{\text{atm}}(\lambda)[L_s(\lambda) + L_w^*(\lambda)] \tag{2}
\]

\( T_{\text{atm}} \) in (2) is the transmittance of absorbing gases, essentially associated with the presence of the ozone layer, twice crossed:

\[
T_{\text{atm}}(\lambda) = \exp \left[-\sum_{j=1}^{\infty} \frac{1}{j} F(\lambda) \tau(\lambda) \omega(\lambda) T_{\text{atm}}(\lambda) \right] \tag{3}
\]

where \( \tau_{\text{atm}}(\lambda) \) is the optical thickness due to absorption.

\( L_s \) and \( L_w^* \) in (2) are the radiance differences, respectively, to scattering by aerosol particles and Rayleigh scattering by molecules. \( L_a \) and \( L_r \) are both given by (with \( x = a \) or \( r \)):

\[
L_s(\lambda) = (1/4\pi \cos \theta) F_s(\lambda) \tau(\lambda) \omega(\lambda) P_s(\theta, \theta_o, \lambda) \tag{4}
\]

where \( F_s(\lambda) \) is the instantaneous solar irradiance above the atmosphere; \( \tau(\lambda) \) is the optical thickness and \( \omega(\lambda) \) the single-scattering albedo for \( x \), with \( \omega_r = 1 \) and \( \omega_a = 1 \) for nonabsorbing aerosol; and

\[
P_s(\theta, \theta_o, \lambda) = P_s(\gamma^-, \lambda) + [\rho(\theta) + \rho(\theta_o)] P_s(\gamma^+, \lambda)
\]

where \( \rho(\theta) \) is the Fresnel reflectance at the air-sea interface and \( P_s \) is the scattering phase function. The two terms in \( P_s \) are for photons backscattered without and with reflection at the sea surface. The corresponding scattering angles are given by

\[
\cos \gamma^\pm = \pm \cos \theta \cos \theta_o - \sin \theta \sin \theta_o \cos (\phi)
\]

If the weak depolarization factor is neglected, the Rayleigh phase function is

\[
P_s(\gamma^\pm) = (3/4)(1 + \cos^2 \gamma^\pm)
\]

The aerosol phase function depends upon the particle size distribution and chemical composition and has no general form.

Marine Signal

\( L_w^* \), the oceanic contribution to \( L_s \) in (1), is related to the water-leaving radiances \( L_{\text{w}} \) by

\[
L_w^*(\lambda) = t(\lambda)L_{\text{w}}(\lambda) \tag{5}
\]

where \( t \), the diffuse transmittance of the atmosphere in the direction of the sensor [Gordon and Morel, 1983], is expressed as

\[
t(\lambda) = \exp[-(1 - \omega_a f_a \tau(\lambda) + (1 - \omega_r f_r \tau(\lambda) + \tau_{\text{atm}}(\lambda))/\cos \theta \tag{6}
\]

where \( f_a \) is the probability of scattering in the forward hemisphere, with \( f_a = 0.5 \) and \( f_r > 0.9 \), so that a nonabsorbing aerosol has no significant influence on the diffuse transmittance; and \( L_w^* \) is due to photons originating from beneath the sea surface and is given by (see, e.g., Gordon and Clark [1981])

\[
L_w^*(\lambda) = [(1 - \rho(\theta))/\cos \theta(1 - \rho) \cos \theta_0 F_s(\lambda) R(\lambda) \tag{7}
\]

where \( m \) is the refraction coefficient of salt water (\( m = 1.333 \)); \( \rho \) is that part of the albedo of a calm sea surface which is only due to specular reflection of the Sun and skylight (its value, which results from averaging the Fresnel coefficients over all angles, is put equal to 0.06); \( \tau_{\text{atm}}(\lambda) \) is the diffuse transmittance of the atmosphere for downwelling solar radiation (\( \tau_0 \) is given by (6) with \( \theta \) replaced by \( \theta_0 \)); \( Q \), the underwater radiance-to-irradiance ratio, would be \( \pi \) for a perfect Lambertian reflector (here, \( Q = 4.5 \), as in the work by Bricaud and Morel [1987]); and \( R(\lambda) \) is the ocean reflectance at null depth, i.e., the ratio of upwelling to downwelling irradiance just below the surface.

Through (5) and (7) \( L_w^* \) may be related to \( R \) by

\[
L_w^*(\lambda) = R(\lambda)t(\lambda)\tau(\lambda)F_s(\lambda)G \tag{8}
\]

where \( G \) is a geometrical factor expressed as

\[
G = \cos \theta_0(1 - \rho)[(1 - \rho(\theta))/m^2 Q
\]

The product \( t(\lambda)\tau(\lambda) \) may be rewritten

\[
t(\lambda)\tau(\lambda) = T_{\text{atm}}(\lambda)T_{\text{w}}(\lambda)
\]

where \( T_{\text{w}} \) is the transmittance associated with scattering by molecules: \( T_{\text{w}} \) is identical to \( T_{\text{atm}} \) (in (3)) with \( \tau_{\text{atm}} \) replaced by \( \tau_{\text{w}}/2 \). The advantage of such a rearrangement is that pressure and ozone influences on atmospheric transmission are decoupled.

The relationship between \( L_w^* \) and \( R \) will be used hereafter is then

\[
L_w^*(\lambda) = R(\lambda)T_{\text{w}}(\lambda)T_{\text{s}}(\lambda)F_s(\lambda)G \tag{8}
\]

3. GENERAL SCHEME

A modeled ocean-atmosphere system, the two parts of which are successively described below, is used to compute the radiances a spaceborne sensor aiming downward would measure in different channels (those of CZCS taken as an example). These radiances are then used as inputs for simulating a VRS processing through a “standard” atmosphere (with respect to its ground pressure and total ozone content) and under the same lighting conditions. This procedure allows the retrieved ocean to be compared with the initial modeled one. This general scheme is represented in Figure 1; the initial
Oceanic Model

In most offshore waters the only optically active constituents, besides the water itself, are the phytoplankton cells and their immediate associated detrital material. For such "case 1" waters [Morel and Prieur, 1977] the reflectance was computed in the CZCS spectral bands as a function of the pigment concentration, \( C = \text{chlorophyll a + phaeopigment a, in milligrams per cubic meter} \) [Bricaud and Morel, 1987; Morel, 1988] in the range 0.015-20 mg/m\(^3\), which includes most of the oceanic situations (Figure 2a).

Given the extraterrestrial solar irradiance and the transmission of the overlying atmosphere, water-leaving radiances are computed for selected values of C, according to (7).

The reflectance model which provides \( R(\lambda) \) values as a function of \( C \) may be conversely used to derive the value of the pigment concentration as a function of the blue-to-green reflectance ratio (curve 1 in Figure 2b). This method for relating pigments and optical quantities differs from the "classical" pigment algorithms which consist of using statistical relationships established between pigments and reflectance ratio by linear regressions on log-transformed data (see, for example, Clark [1981]). These algorithms were not used here, because they would have introduced an artifactual discrepancy between the method for creating the initial ocean \( R(\lambda) \) as a function of \( C \) and the inverse method for retrieving \( C \) from the reflectance ratio. This discrepancy would have particularly occurred at low and high concentrations where the modeled relationship and statistical algorithm (respectively curves 1 and 2 in Figure 2b) diverge. The simulation, directed to explore atmospheric effects, is then made under the assumption of a "perfect" pigment algorithm.

Atmospheric Model

The transmittance and Rayleigh scattering are computed according to (3) and (4). The extraterrestrial solar irradiances \( F(\lambda) \) for the CZCS channels are those of Gordon et al. [1983]. Standard values of the Rayleigh optical thickness, \( \tau_r \), and of that due to absorbing gases, \( \tau_{ap} \), are yearly averages of those recommended for mid-latitudes by Systems and Applied Sciences Corporation (SASC) [N.A.S.A. 1981] and are given in Table 1. The origin of these values was not specified by SASC and, in particular, the adopted values of pressure and ozone content were not given. It is assumed that the yearly averages, \( \tau_r \) and \( \tau_{ap} \), correspond, respectively, to a standard pressure of 1013 hPa and an ozone content of 340 matm cm [or Dobson units (DU)].

The Rayleigh optical thickness being directly proportional to the ground pressure, the actual value, \( \tau_r \), is computed according to

\[
\tau_r(\lambda) = \tau_r(\lambda_0)(1 + \Delta p/p)
\]

where the departure \( \Delta p \) of the actual pressure with respect to the standard is set equal to \( \pm 15 \) hPa.

<table>
<thead>
<tr>
<th>CZCS Channel</th>
<th>( \lambda, ) nm</th>
<th>( \tau_{ap} )</th>
<th>( \tau_r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>443 ± 10</td>
<td>0.0068</td>
<td>0.2314</td>
</tr>
<tr>
<td>3</td>
<td>550 ± 10</td>
<td>0.0356</td>
<td>0.0963</td>
</tr>
<tr>
<td>4</td>
<td>670 ± 10</td>
<td>0.0208</td>
<td>0.0441</td>
</tr>
</tbody>
</table>

Numerical computations are made in two (favorable/ unfavorable) geometrical configurations and for the CZCS channels 1 (443 ± 10 nm), 3 (550 ± 10 nm), and 4 (670 ± 10 nm). Channel 2 (520 ± 10 nm) is not considered, because it would not add any information in the frame of such a sensitivity study.

Fig. 2. (a) Modeled marine reflectances in CZCS channels 1 (443 ± 10 nm), 3 (550 ± 10 nm), and 4 (670 ± 10 nm) as a function of the pigment concentration (chl a + phaeo a). (b) Modeled (curve 1) and statistical (curve 2) relationships between the blue-to-green reflectance ratio and the pigment concentration.
TABLE 2. Values of the Aerosol Angström Exponent, n, and Aerosol Load, F, in the Actual Atmosphere and of the Angles \( \theta, \theta_0, \) and \( \phi \) (in Degrees) for Four Selected VIRS Situations

<table>
<thead>
<tr>
<th>Set</th>
<th>n</th>
<th>F</th>
<th>( \theta )</th>
<th>( \theta_0 )</th>
<th>( \phi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0.5</td>
<td>30</td>
<td>0</td>
<td>90</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>0.3</td>
<td>30</td>
<td>60</td>
<td>120</td>
</tr>
<tr>
<td>3</td>
<td>0.5</td>
<td>0.5</td>
<td>30</td>
<td>0</td>
<td>90</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>0.1</td>
<td>30</td>
<td>0</td>
<td>90</td>
</tr>
</tbody>
</table>

The value \( F = 0.3 \) for situation 2 is such that the aerosol optical thickness is the same as that for situations 1 and 3.

The actual value of \( \tau_{ag} \) is obtained by adding an ozone content “perturbation” to the standard value

\[
\tau_{ag}(\lambda) = \tilde{\tau}_{ag}(\lambda) + \sigma_O(\lambda) \Delta(O_3)
\]

where the perturbation \( \Delta(O_3) \) is set equal to \( \pm 50 \text{ DU} \) and the molecular absorption cross sections \( \sigma_O \) are those of Nicolet [1981], weighted for spectral response of CZCS channels.

In the modeled atmosphere the radiances due to (nonabsorbing) aerosol are computed according to (4) by assuming that (1) the optical thickness \( \tau_a \) varies with the wavelength according to

\[
\tau_a(\lambda) = \tau_a(\lambda_0)(\lambda/\lambda_0)^{-n}
\]

where the Angström exponent \( n \) is assigned to be 0 or 1 and (2) the scattering varies with angle according to a two-term Heney-Greenstein phase function

\[
P_s(\gamma, \chi) = f(\gamma, \chi, g_1) + (1 - x)f(\gamma, \chi, g_2)
\]

where \( f(\gamma, \chi) = (1 - g)((1 + g - 2g\cos \gamma^{2})^{3/2} \) and \( x = 0.983, \ g_1 = 0.82, \ g_2 = -0.55 \) as in the work by Sturm [1981] and Gordon and Castaño [1987].

In order to preserve the generality of the results, we avoid using absolute values of the aerosol phase function \( P_a \) would be necessary if directly applying (10)) and define an operational turbidity index as

\[
F = L_a(\lambda_0)/L_a(\lambda_0)
\]

which is given the values 0.1 or 0.5 (for an aerosol exhibiting the phase function (10), the corresponding \( \tau_{ag}(550) \) values would be, respectively, 0.056 and 0.283). With the selected values for \( F, L_a(550) \) is computed using (11), with \( L_a(550) \) from (4). Changing of wavelength is effected through (9) and changing of geometry through (10).

Among the possible combinations of the parameter values, i.e., the aerosol load \( F \), the aerosol Angström exponent \( n \), and the geometrical configuration, four situations have been selected (Table 2) as follows. Set 1 is thought of as a reference set: The atmosphere is moderately loaded by an aerosol of current spectral selectivity and the constellation is favorable (Sun and spacecraft not too far from zenith). Set 2 is designed to explore the sensitivity of the pressure and ozone effects to the geometry in which remote sensing is effected. In comparison to set 1 the constellation 2 is unfavorable, in the sense that air masses are greater. Set 3 differs from the reference set only by the nature of the aerosol exhibiting a nonselective scattering. Set 4 differs from the reference set only by the aerosol load, which is that of very clear atmospheres. Henceforth the numbering of the curves (in Figures 3 to 5) will coincide with the numbering of the situations in Table 2.

4. EFFECTS OF PRESSURE AND OZONE:

**Available Aerosol Case**

The total signal above the actual atmosphere may be written through (1), (2), and (8):

\[
L_r = (L_{r'} + L_{a})T_{ag} + RT_{ag}T_rF,G
\]

(Note that all terms but \( G \) in (12) are wavelength-dependent. Henceforth the explicit dependence is omitted within the equations.)

The radiances and transmittances computed by assuming a standard atmosphere (primed symbols) necessarily differ from their actual values, which include the effect of a pressure or ozone perturbation. Remote sensing simulated through the standard atmosphere leads therefore to a retrieved marine reflectance \( R(\lambda) \) which may differ from the initial value \( R(\lambda) \).

Rewriting (12) for the standard atmosphere gives

\[
L_r = (L_{r'} + L_{ag})T_{ag} + RT_{ag}T_rF,G
\]

which, compared to (12), gives

\[
(RT_{ag}T_r' - RT_{ag}T_r')F,G = T_{ag}(L_{r'} + L_{ag}) - T_{ag}(L_{r'} + L_{ag})
\]

In this section the aerosol contribution \( L_{ag}(\lambda) \) is assumed to be known so that \( L_{ag}(\lambda) = L_{ag}(\lambda) \).

**Pressure**

With \( p \) differing from \( \tilde{p} \), \( \tau_{ag}(\lambda) \) differs from \( \tilde{\tau}_{ag}(\lambda) \) and \( L_{ag}(\lambda) \) differs from \( L_{ag}(\lambda) \) in (13), the relative error on the Rayleigh signal being equal to \( \Delta p/p \). \( T_r(\lambda) \) also differs from \( T_r(\lambda) \), while \( T_{ag}(\lambda) \) remains unaffected.

The retrieved reflectance \( R(\lambda) \) is, from (13),

\[
R' = (T_r/T_r')R + (L_{r'} - L_{ag})/GF,T_r'
\]

The extent to which \( R'(\lambda) \) differs from \( R(\lambda) \) is independent from the aerosol. As long as \( T_r/T_r' \) does not significantly differ from 1 (\( T_r' - T_r < 0.5\% \) when \( \Delta p = \pm 15 \text{ hPa} \), the difference between \( R \) and \( R' \) is directly proportional to that between the Rayleigh radiances and can be written

\[
\Delta R = R' - R = (L_{r'} - L_{ag})/GF,T_r' = -\Delta L_r/GF,T_r'
\]

\( AR(\lambda) \) decreases with increasing wavelength, and accordingly the blue-to-green ratio used to derive the pigment concentration is affected and the retrieved \( C' \) differs from \( C \). A positive (negative) pressure departure leads to an overestimate (underestimate) of low pigment concentrations and conversely to an underestimate (overestimate) of high concentrations.

The variations of the ratio \( C'/C \) with \( C \) are presented in Figure 3a for pressure departures \( \Delta p = \pm 15 \text{ hPa} \) and for the four situations of Table 2. Because of the nonlinear pigment-to-reflectance relationships (and, to a much lesser extent, because of the exponential nature of the transmission terms) the curves for \( +\Delta p \) and \( -\Delta p \) are not rigorously symmetrical. \( C' \) remains close to \( C \) only in a rather narrow range of concentration, around a value, \( C_o \), for which there is no mistemate. This occurs when the additional Rayleigh signal (positive or negative) associated with \( \Delta p \) exhibits the same blue-to-green ratio as does the water with a given pigment concentration \( C_o \).

At \( C = C_o \),

\[
R(443)/R(550) = R(443)/R(550) = \Delta R(443)/\Delta R(550)
\]
Developing $\Delta R$ according to (14) leads to

$$R(443)/R(550) = \left[ L_s(443)/L_s(550) \right] \times \left[ F_s(550)/F_s(443) \right] \times \left[ T_s(443)/T_s(550) \right]$$

which equals 2.3 with the adopted values and corresponds to $C_0 = 0.2 \text{ mg/m}^3$.

For $C$ values lower and greater than $C_0$, the pigment retrieval is more and more affected, with $C'$ differing from $C$ by a factor up to 2 for the smallest $C$ values ($<0.02 \text{ mg/m}^3$) and more than 2 for $C$ greater than 4–5 mg/m$^3$. As situations 1, 3, and 4 differ only by the aerosol load or exponent (from which $R'$ is independent), the corresponding curves 1, 3, and 4 are confounded. In the unfavorable constellation (curve 2), the effect of the pressure perturbation is slightly enhanced.

**Ozone**

When the actual content ($O_3$) departs from the standard ($O_{30}$), $T_{so}(\lambda)$ differs from $T_{yo}(\lambda)$ in the expression giving $R'(\lambda)$ (equation (13)), whereas all other terms remain unchanged. Therefore

$$R' = (T_{so}/T_{yo}) R + (T_{yo} - T_{so})(L_o + L_y)/G F_s$$

(15)

$R'(\lambda)$ is significantly affected only in the green part of the spectrum (i.e., at 550 nm) where ozone absorption is maximum. The blue-to-green ratio is modified and therefore the retrieved pigment concentration $C'$ differs from the actual one, $C$. With $L_o$ appearing in (15), the error in the marine reflectance depends upon the aerosol signal and increases with increasing load.

The results for $\Delta(O_3) = \pm 50 \text{ DU}$ are presented (Figure 3b) for the four selected situations. For a given ozone departure the bias in the pigment retrieval remains of constant sign throughout the whole $C$ range (i.e., the error cannot be 0 as in the case of a pressure departure). A positive (negative) $\Delta(O_3)$ provokes an underestimate (overestimate) of the pigment concentration. As previously for opposite $\Delta p$, the curves for opposite $\Delta(O_3)$ are not strictly symmetrical. In all cases the error takes its minimum values, of the order of 25–30% (for $\Delta(O_3) = \pm 50 \text{ DU}$), for $C$ values in the range 0.1 to 2–3 mg/m$^3$. In worst cases, however, the retrieved $C'$ may differ from the actual value $C$ by a factor of 2 at high $C$ values, and even more at low $C$ values.

When the aerosol load is reduced ($F$ is 0.1 for curve 4 instead of 0.5 for curve 1), the error is reduced, while it increases when the geometry becomes unfavorable (curve 2). When the exponent $n$ is given the value 0, the $C'/C$ ratio is changed by less than 1% and curves 1 and 3 cannot be distinguished.

5. **Effects of Ozone and Pressure:**

**Unavailable Aerosol Case**

Without any information concerning the aerosol type and concentration in the standard atmosphere, (4) is of little use for computing the radiances $L_s(\lambda)$, which have to be extracted from the total signals $L_s(\lambda)$ simultaneously with the marine signals $L_m(\lambda)$. Briefly, there are more unknowns than equations (equation (1) written at three wavelengths) in the problem to be solved, so that additional information must arbitrarily be introduced:

1. An algorithm which relates the marine signals at various wavelengths provides successive reestimates of the signal in the red (670 nm) as a function of those in the blue (443 nm) and green (550 nm). A classical method consists of using a statistical relationship between the blue-to-red ratio ($L_m(443)/L_m(670)$) and the blue-to-green ratio ($L_m(443)/L_m(550)$) (as derived from linear regression on the log transforms of sea truth data [see Smith and Wilson, 1981]). Such a statistical algorithm has not been used in the present study, because it would have again introduced an artificial discrepancy between, on one hand, the method for relating pigment concentrations and marine signals, and, on the other hand, the method for interrelating these signals. The reflectance model has then been used to relate the blue-to-red ratio, $R'(443)/R(670)$, to the blue-to-green ratio, $R'(443)/R'(550)$.

2. The aerosol radiances are supposed to vary spectrally according to a power law (equation (9)). The exponent is itself an unknown and is internally estimated by iterations from the ratio of the aerosol radiances at 550 and 670 nm when the pigment concentration in the pixel under consideration is within the range 0.015–1 mg/m$^3$. The technique for deriving the exponent and for retrieving the pigment concentration fol-
TABLE 3a. Retrieved Values of the Angström Exponent, $n'$, Averaged Over the C Range 0.015–1 mg/m$^3$ for $\Delta p = \pm 15$ hPa

<table>
<thead>
<tr>
<th>Set</th>
<th>$\Delta p = +15$ hPa</th>
<th>$\Delta p = -15$ hPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.07 ± 0.001</td>
<td>0.93 ± 0.002</td>
</tr>
<tr>
<td>2</td>
<td>1.12 ± 0.002</td>
<td>0.87 ± 0.003</td>
</tr>
<tr>
<td>3</td>
<td>0.99 ± 0.002</td>
<td>-0.10 ± 0.003</td>
</tr>
<tr>
<td>4</td>
<td>1.32 ± 0.005</td>
<td>0.56 ± 0.011</td>
</tr>
</tbody>
</table>

Values are for the four situations of Table 2.

lows that described by Bricaud and Morel [1987], except that the modeled reflectance relationships are used instead of the statistical ones.

The iterative algorithms are designed to partition the total radiances into an atmospheric and an oceanic contribution. After the Rayleigh signal has been computed by applying (4), the remaining radiances, $L'(\lambda)$, to be shared between aerosol and ocean are

$$L' = L_{a} - T_{a}L'_{a} = T_{a}L'_{a} + T_{a}G_{F}F'$$  (16)

As a consequence, any introduced error ("pressure" errors in $L'$ and $T_{a}$, or "ozone" error in $T_{a}L'_{a}$) will be diversely shared itself between aerosol and ocean. It does not react entirely on the marine reflectances, as was the case when the aerosol was assumed to be known.

**Pressure**

With an actual pressure value differing from the standard value, the radiances $L'(\lambda)$ to be processed differ from $L(\lambda)$ in the actual system, and the retrieved value $n'$ of the Angström exponent will differ from the input value $n$. The results for $n'$ when $\Delta p = \pm 15$ hPa are presented in Table 3a for the four selected situations. The extent to which $n'$ differs from $n$ depends only weakly upon the pigment concentration (in the range 0.015–1 mg/m$^3$), so that the computed $n'$ values have been averaged over this range. For a positive (negative) pressure departure, the exponent is underestimated (overestimated). It is retrieved within 10% in a moderately loaded atmosphere seen in good geometric conditions, and whether the initial value is 1 (set 1) or 0 (set 3). In unfavorable geometrical conditions the error becomes slightly greater (set 2) while it is much more increased (of the order of 30%) when the aerosol load is reduced from 0.5 (for situations 1 to 3) to 0.1 (set 4).

With the erroneous $n'$ values which have been computed in each case, the processing is pursued to retrieve the aerosol load $F'$ together with the pigment concentrations $C'$ for the whole range of oceanic situations (0.015–20 mg/m$^3$).

It must be noted here that the value of the Angström exponent which is computed is only in the restricted range 0.015–1 mg/m$^3$, but is used afterward in the pigment retrieval processing over the full range 0.015–20 mg/m$^3$. This tends to simulate the actual CZCS processing and implies that for any oceanic pixel where the exponent cannot be computed (for any $C$ value greater than 1 mg/m$^3$) there would exist a "clear water" ($C < 1$ mg/m$^3$) area near enough to this pixel to be overlayed by the same atmosphere (with respect to pressure and aerosol exponent) and seen in close geometrical conditions.

As occurred for the Angström exponent (over the $C$ range 0.015–1 mg/m$^3$), the aerosol load retrieval is only weakly sensitive to the pigment concentration (throughout the full range 0.015–20 mg/m$^3$). The averaged values of the retrieved to-initial load ratio, $F'/F$, computed when $\Delta p = \pm 15$ hPa in each situation of Table 2 are listed in Table 3b. When the geometry is favorable and the atmosphere moderately loaded (sets 1 and 3) the retrieved load is erroneous by about 5%, whatever the exponent value. Changing the geometry to the unfavorable one increases the error a little (5% for set 2) but much less than changing the load from 0.5 (sets 1 to 3) to the value 0.1 of set 4, for which the error is maximum (18%).

With respect to the retrieved pigment concentration the results for $\Delta p = \pm 15$ hPa are presented in Figure 4a. In all situations (curves 1 to 4) a positive (negative) pressure perturbation leads to an underestimate (overestimate) of the whole C range. When the actual pigment concentration is less than 3–4 mg/m$^3$, it is retrieved within 10–15%, while the error increases rapidly at higher C, exceeding a factor of 2 when C > 10 mg/m$^3$. At a given C value the error is minimum for the reference parameter set (curve 1) and grows slightly when the geometry is less favorable (curve 2) and when the exponent n is changed from 1 to 0 (curve 3). A peculiar feature is that the misestimate is practically the same when the load $C = 0.5$ or 0.1 (curves 1 and 4 cannot be distinguished), although the error in the exponent retrieval was considerably greater when the aerosol load was minimum (see Table 3a).

When comparing the results of Figure 4a (UA case) to those of Figure 3a (AA case) it is interesting to note that except in the vicinity of $C_{0} = 0.2$ mg/m$^3$, the complete knowledge of the aerosol (AA case) leads to errors much greater than when the aerosol has to be derived together with the pigment concentration.

**Ozone**

The effect of an ozone perturbation superimposed upon the standard value is quite different, because ozone acts significantly only in the green channel. Concerning the retrieved exponent $n'$, the results are listed in Table 4a for the four selected situations when $\Delta(O_{3}) = \pm 50$ DU. The way the exponent is affected varies only weakly with C in the range 0.015–1 mg/m$^3$ and, as previously for $\pm \Delta p$, the computed $n'$ values have been averaged over this range. For a positive (negative) perturbation the exponent is underestimated (overestimated). Values of $n'$ differ from $n$ by less than 10% in a moderately loaded atmosphere seen in good geometric conditions whatever the n value (sets 1 and 3). In unfavorable geometrical conditions the error becomes slightly greater (set 2) and is much higher (approximately 25%) when the load is reduced from 0.5 (for situations 1 to 3) to 0.1 (set 4).

The average $n'$ value in each situation is then used to retrieve the aerosol load simultaneously with the pigments over the full C range 0.015–20 mg/m$^3$. Table 4b lists the values of the retrieved-to-initial aerosol load ratio for $\Delta(O_{3}) = \pm 50$ DU and for the four selected situations. As previously for $\Delta p$, the influence of the initial C value on the retrieved load is weak enough to be neglected, and the results presented are average values over the C range 0.015–20 mg/m$^3$. The retrieved load

TABLE 3b. Retrieved-to-Initial Aerosol Load Ratio Averaged Over the C Range 0.015–20 mg/m$^3$ for $\Delta p = \pm 15$ hPa

<table>
<thead>
<tr>
<th>Set</th>
<th>$\Delta p = +15$ hPa</th>
<th>$\Delta p = -15$ hPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.05 ± 0.001</td>
<td>0.95 ± 0.001</td>
</tr>
<tr>
<td>2</td>
<td>1.07 ± 0.002</td>
<td>0.93 ± 0.002</td>
</tr>
<tr>
<td>3</td>
<td>1.05 ± 0.001</td>
<td>0.95 ± 0.001</td>
</tr>
<tr>
<td>4</td>
<td>1.18 ± 0.005</td>
<td>0.82 ± 0.005</td>
</tr>
</tbody>
</table>

Values are for the four situations of Table 2.
Fig. 4. Unavailable aerosol case. Retrieved-to-initial pigment concentration ratio as a function of the initial concentration and for the four situations of Table 2 (curves 1–4) (a) for Δp = ±15 hPa and the computed values of the Angström exponent in Table 3a and (b) Δ(O3) = ±50 DU and the computed values of the Angström exponent in Table 4a. Beyond 2 mg m\(^{-3}\), dashed lines replace solid lines, since this C region is hardly reachable with the 443/550-nm algorithm when applied to CZCS data (the same convention is adopted for Figures 5 and 6).

differs from the initial value by 10%, at the most. This maximum error occurs when the F value to be retrieved is that of very clear atmospheres, exemplified by set 4.

With respect to the retrieved pigment concentration the results for Δ(O3) = ±50 DU are presented on Figure 4b. A positive (negative) ozone departure leads to an underestimate (overestimate) of the pigment concentration throughout the whole range. The error is the lowest, yet of the order of 30%, for C between 0.05 and 1 mg/m\(^3\). It increases drastically at higher C to exceed a factor of 2 in all cases when C > 8–10 mg/m\(^3\). The factor of 2 could also be reached, in worst cases, for very low C. At a given C value the error is minimum for the situation corresponding to the lowest aerosol load and favorable geometry (curve 4). It slightly increases when the load is increased (curve 1) or when the geometry is less favorable (curve 2). It has to be noted that the error on C′ is not sensitive to the value of the Angström exponent and curves 1 and 3 are confounded. When the results are compared to those obtained for the AA case (Figure 3b), it appears that the iterative procedure leads to smaller errors for low C (<0.2 mg/m\(^3\)) while the complete knowledge of the aerosol is more favorable for high C.

6. Discussion

1. There is not a single and standardized method to process the CZCS data, but several ones differing from author to author. Therefore the question which could arise is, Are the results concerning the unavailable aerosol case (CZCS simulation) restricted to, and only of interest for, the specific method we are using when processing the CZCS data? As a matter of fact, the various methods are similar as soon as they include iterative algorithms resting on the existence of interrelationships (statistical or modeled) between the marine signals at three wavelengths (see, e.g., Smith and Wilson [1981] and Bricaud and Morel [1987]). The edge point from which the various methods gradually diverge is the way of deriving the "best" Angström exponent and of using this value (on a pixel-by-pixel basis, or as an averaged value over a subscene of variable size).

The value of this exponent (n′ in Tables 3a and 4a) obtained when simulating the UA case, and therefore the discrepancies between C and C′, can be regarded as a particular product of the method. With this possible objection in mind the UA case simulation has been run again with a slight modification, which consists of changing n′ and, in effect, of assigning to this exponent its initial "true" value n. This computation tends to simulate a situation where the exponent should have been perfectly assessed, the aerosol load, however, remaining an unknown.

The results for Δp = ±15 hPa and for the four selected situations are shown in Figure 5a. They look like those in Figure 3a (AA case) with, however, significantly smaller errors occurring at low C values (C < 0.1 mg/m\(^3\)). The errors, identical in the clear and the moderately loaded atmospheres (curves 1 and 4), increase when the geometry becomes un-

<table>
<thead>
<tr>
<th>Set</th>
<th>Δ(O3) = +50 DU</th>
<th>Δ(O3) = -50 DU</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.98 ± 0.003</td>
<td>1.02 ± 0.004</td>
</tr>
<tr>
<td>2</td>
<td>0.97 ± 0.005</td>
<td>1.03 ± 0.011</td>
</tr>
<tr>
<td>3</td>
<td>0.98 ± 0.002</td>
<td>1.02 ± 0.003</td>
</tr>
<tr>
<td>4</td>
<td>0.94 ± 0.010</td>
<td>1.06 ± 0.015</td>
</tr>
</tbody>
</table>

Values are for the four situations of Table 2.
future sensors designed for an improved accuracy. When actual pressure is ignored, the relative error on $L_R$ is essentially the same whether $L_R$ is accurately (multiple scattering) or approximately (single scattering) computed; therefore the results of the present sensitivity study are unaffected. (Gordon et al. [1988] recently developed a scheme for including pressure variations in the exact multiple scattering computation of $L_R$).

3. The CZCS signals are 8 bits digitized, and the accuracy of the sensor is roughly at the ±1 digital count level. The effect on the retrieved pigment concentration of such possible errors in the measured signals has been simulated for the UA case when the VRS situation is that of set 1 in Table 2. The results are presented in Figure 6, where the curves correspond to a noise of ±1 digital count superimposed on the actual values of the signals at spacecraft level, in the blue and/or green CZCS channels. (At CZCS gain 1 one digital count corresponds, respectively, to 0.0445 and 0.0248 mW m$^{-2}$ sr$^{-1}$ μm$^{-1}$ in channels 1 and 3). From the strict viewpoint of 8 bits limitation the retrieved pigment concentration is then expected to be randomly affected by an error up to a factor of 2 (low concentrations) or even 3 (very high concentrations). The pressure and ozone effects discussed above do not surpass this magnitude, and therefore it could be inferred that a due attention to these effects is not crucial. Nevertheless, the limitations in the radiometric accuracy affect the final VRS product (i.e., a map of the phytoplankton concentration) as an erratic noise, while neglecting the structures in the ozone content or pressure distributions may generate systematic biases or produce artificial structures in the retrieved phytoplankton distribution.

With regard to future visible sensors, designed for an improved radiometric accuracy, the problem is simpler. The ±1 numerical count level for 10 bits-digitized signals would produce a stochastic error on the measured values lower by a factor of 4 than that of CZCS with the consequence of emphasizing the importance of properly correcting for the pressure and ozone influences.
7. CONCLUSIONS

Unavailable Aerosol Case

The occurrence of an ignored pressure perturbation may lead to unacceptable biases in the phytoplankton content estimate and mapping. The magnitude of the error depends on the concentration to be retrieved and on the way the aerosol exponent has been obtained. Whatever the method, the CZCS scenes which include mesotrophic or eutrophic waters (C > 3–4 mg/m³) would have to be processed by taking into account actual pressure variations. This does not give rise to unsolvable practical problems, since this information is available on a regular and synoptic basis through several weather forecast or meteorological institutions.

Ignored ozone content perturbations can strongly bias the pigment content estimate in the case of waters with very low or high algal content, so that the actual values should be introduced in the processing. On board Nimbus 7, the total ozone mapping system (TOMS) provides the necessary and contemporaneous information with sufficient accuracy [see Krueger et al., 1981] for VRS purposes; follow-on ozone sensors could serve when future ocean color instruments will become operational.

Available Aerosol Case

With respect to CZCS, future visible sensors (e.g., Vegetation and Sea Wide Field Sensor (Sea WiFS)) are in principle designed to achieve an improved atmospheric (aerosol) correction, thanks to the incorporation of dedicated near-IR channels, as well as a better radiometric accuracy. Assigning mean climatic values to varying barometric pressure or ozone content would be inconsistent with the expected increase in the quality of the future visible imagery products.

In addition to pressure and ozone content variations, that of the NO₂ content would also have to be considered for processing improved data from visible sensors. NO₂ is an absorber in the visible range (in the blue part only), and the reported values of the columnar amount could vary within 1 order of magnitude [Shaw, 1976]. The expected consequences of such variations on the pigment retrieval are much less severe than those due to ozone since the NO₂ absorbing effect remains weak, albeit severe enough to damage the designed quality.

REFERENCES


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