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A semi-analytical radiative transfer model to simulate the specific intensity of sunlight reflected by the atmosphere and ocean

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In order to retrieve near-surface phytoplankton pigment concentration from ocean color data collected during the 1991-1992 Research on Antarctic Coastal Ecosystem Rates (RACER) campaign, a fast, yet accurate radiative transfer model of the specific intensity of sunlight reflected by the atmosphere and ocean (including backscattering by the water body) is required. This model must run fast because of the large amount of data to be processed, which prevents the use of Monte Carlo, successive orders of scattering codes, or any computer-intensive code. Although this model must include simplifying assumptions, it will retain the essential physics of the problem. We have built such a model.

The purpose of this brief report is to present the model, to examine the relative influence of the input parameters, to use the model to simulate actual aircraft data, and to discuss improvements as well as future validation activities.

We consider the case of a plane-parallel, vertically heterogeneous, spatially homogeneous atmosphere bounded by a wavy interface. Below the interface, the ocean is assumed to be homogeneous and infinite vertically (no bottom effects). We focus on one Stokes parameter only, namely, the specific intensity of the reflected sunlight or, equivalently, the apparent reflectance (specific intensity normalized by incident solar irradiance). Polarization is therefore not considered.

Based on Tanré et al. (1979), the apparent reflectance in the visible and near-infrared is modeled as the sum of contributions representing various photon pathways, namely, radiation uniquely backscattered by the atmosphere; direct and diffuse radiation reflected by the ocean and directly transmitted through the atmosphere; direct radiation reflected by the ocean and scattered by the atmosphere; and radiation reflected by the surface and/or scattered by the atmosphere more than twice. Multiple scattering and aerosol-molecule coupling are taken into account, as well as the bidirectional characteristics of the surface. Interactions between scattering and gaseous absorption, however, are neglected, which is justified because gaseous absorption in the spectral range of interest (400 to 900 nanometers) is either weak or occurs at altitudes in which molecules are rarified (case of ozone). Aerosol-molecule coupling is accounted for by making corrections using a tabulated set of exact calculations (with the values obtained when neglecting the coupling). Accounting for surface anisotropy requires the computing of a directionally-averaged reflectance, defined as the normalized integral over viewing angles of the surface reflectance weighted by the downward radiance at the surface (Tanré et al. 1979). In the computations, single-scattering approximation is assumed for the downward radiance at the surface. Atmospheric functions, namely scattering transmission, path radiance, and spherical albedo are approximated by analytical formulas (Tanré et al. 1986).

The surface reflectance includes glitter (fresnel reflection), foam, and water body components. Glitter reflectance is modeled as a function of wind speed and direction, according to Cox and Munk (1954). The effect of foam is parameterized as a function of wind speed (Koepke 1984). Water body reflectance is assumed to be isotropic, and it is modeled as a function of phytoplankton pigment concentration (Morel 1988). In subsequent versions of the model, however, this assumption will be relaxed, and bidirectional effects will be accounted for by using the approximate solutions of Sobolev (1963) (Frouin and Hermanto this issue). The model input parameters, apart from solar and viewing angles, are aerosol type and amount (parameterized as a function of surface visibility), wind speed and direction, and phytoplankton pigment concentration.

Figures 1 and 2 show the results of simulations of the top-of-atmosphere reflectance at the wavelengths of 450 and 850 nanometers, respectively, for a solar zenith angle of 30°, a pigment concentration of 0.03 milligrams per cubic meter, a wind speed of 5 meters per second, a wind direction from 330°, standard maritime aerosols, and a visibility of 23 kilometers. Only variations in the

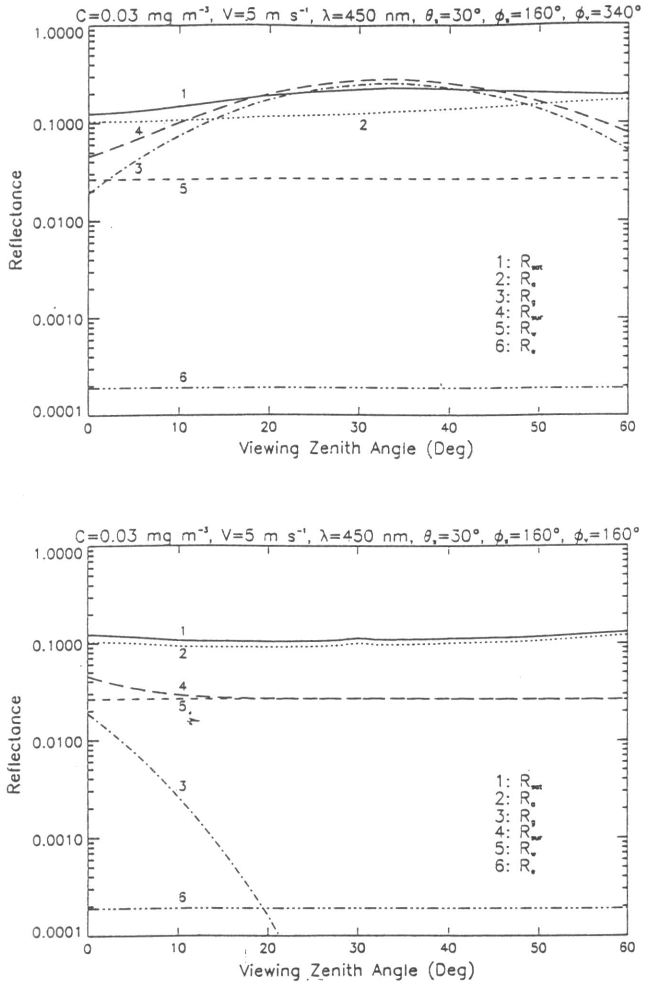

Figure 1. Simulations of the top-of-atmosphere reflectance, R_{sat}, intrinsic atmospheric reflectance, R_a, glitter reflectance, R_g, foam reflectance, R_e, and total surface reflectance R_{sur}, at 450 nanometers in the principal plane as a function of the viewing zenith angle. Forward scattering (*top*), backward scattering (bottom). Solar zenith angle is 30°, visibility is 23 kilometers, aerosols are of maritime type, pigment concentration is 0.03 milligrams per cubic meter, and wind is from 330° at 5 meters per second.

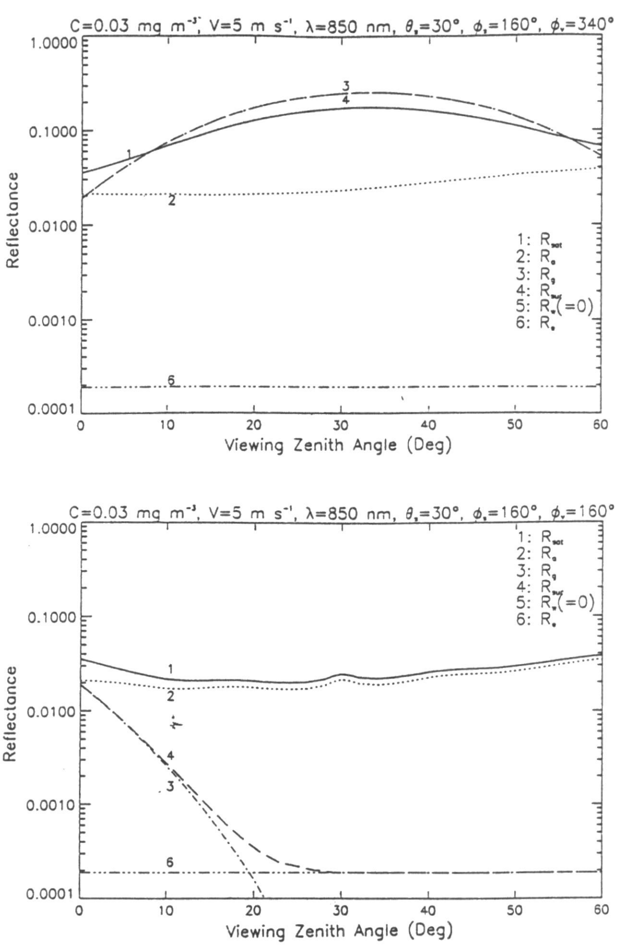

Figure 2. Same as figure 1, except 850 nanometers.

solar principal plane are displayed. In forward-scattering conditions (figure 1, *top* and figure 2, *top*), glitter reflectance dominates the top-of-atmosphere signal. For some viewing angles (specular conditions), the surface reflectance surpasses the top-of-atmosphere reflectances (*curves* labeled 4), but is reduced by atmospheric absorption. In backscattering conditions (figure 1, *bottom* and figure 2, *bottom*), the atmospheric reflectance (*curves* labeled 2) dominates. The glitter reflectance, however, contributes significantly to the top-of-atmosphere reflectance for viewing angles less than 15°. Water body reflectance, about 0.03 at 450 nanometers, has negligible influence at 850 nanometers. The effect of the backward peak of the aerosol phase function is noticeable at a 30° viewing zenith angle, especially at 850 nanometers, where molecular scattering is less active. An interesting feature, not shown here, is the dissymmetry in the +90° and -90° planes due to wind direction. Figures 1 and 2 illustrate the difficulty of ocean-color remote sensing from above the atmosphere because most of the signal (for instance 85 percent at 450 nanometers, see figure 1, *bottom*) originates from the atmosphere and the surface.

We used the coupled ocean-atmosphere model described above to simulate aircraft observations of the ocean made by the polarization and directionality of the earth reflectance (POLDER) instrument on 29 December 1991 over the Gerlache Strait. The POLDER instrument (Frouin et al. this issue) measures the specific intensity and polarization characteristics of reflected sunlight in spectral bands centered at 450, 500, 570, 670, and 850 nanometers. At the altitude of the flight, 3,960 meters feet, the pixel size is 17 x 17 meters. In the calculations, we assumed that the aerosols were located below the aircraft, and we partitioned the amount of air molecules above and below the aircraft according to atmospheric pressure at both the level of the flight and at the surface. For consistency, we normalized the POLDER measurements by the incident solar irradiance computed by also assuming no aerosols above the aircraft.

Figure 3 shows the reflectance measured at 500 and 850 nanometers (*crosses* and *open circles*, respectively) as a function of viewing zenith angle in the solar principal and perpendicular planes. Negative-viewing zenith angles correspond, by defini-

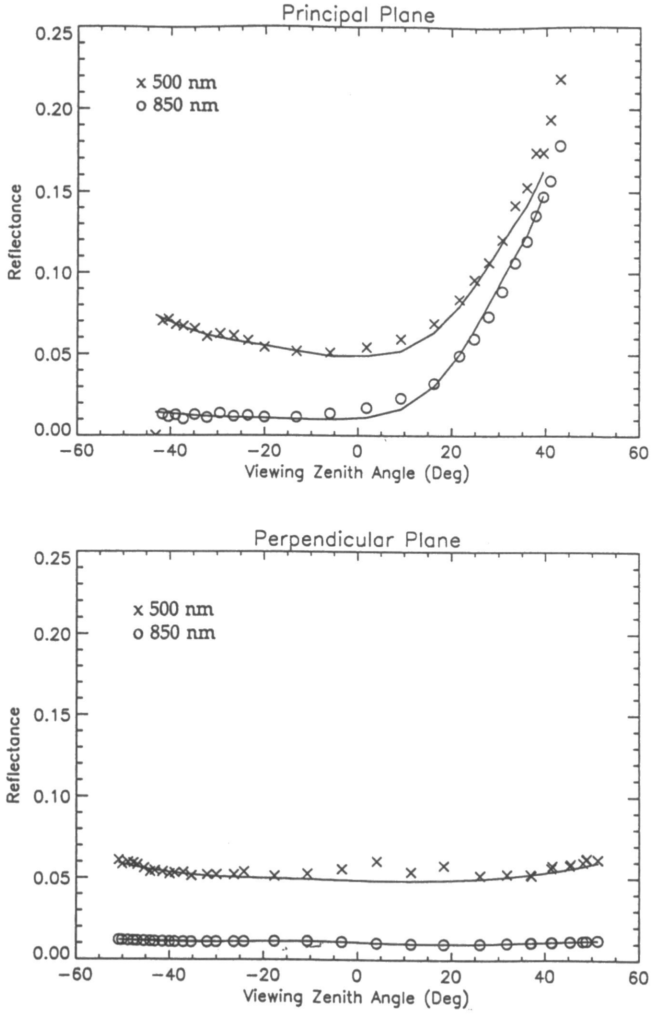

Figure 3. Measured and modeled POLDER reflectance at 500 and 850 nanometers in the solar principal and perpendicular planes (*top* and *bottom*, respectively). Data are represented by *crosses* (500 nanometers) and *open circles* (850 nanometers), and calculated values by *solid lines*. The best fit is obtained for a wind speed of 6.5 meters per second, a wind direction from 215°, an aerosol optical thickness of 0.06 at 550 nanometers, aerosols of water-soluble type, and phytoplankton pigment concentration of 1 milligram per cubic meter.

tion, to relative azimuth angles of 0° (principal plane) or 270° (perpendicular plane). Due to glitter, the reflectance in both bands reaches high values (above 0.15) in the principal plane (forward scattering). The reflectance at 850 nanometers is as low as 0.01 outside the glitter region, already suggesting that aerosol amount is low below the aircraft. Slight, yet non-negligible dissymmetry with respect to nadir viewing is noticed at 850 nanometers—the likely effect of anisotropic wave slope distribution because of wind direction. At 500 nanometers, where phytoplankton pigments absorb significantly, the variations in viewing the zenith angle in the perpendicular plane do not resemble those at 850 nanometers—a manifestation of spatial changes in phytoplankton abundance.

The data are best fit (*solid lines*) when the model is run with a wind speed of 6.5 meters per second, a wind direction from 215°, an aerosol-optical thickness of 0.06 at 550 nanometers, a water-soluble aerosol type, and a phytoplankton pigment concentration of 1 milligram per cubic meter (only affects the reflectance at 550 nanometers). Except for pigment concentration, the values are in general agreement with the in-situ observations made aboard R/V *Polar Duke*, which reported a wind speed of about 10 meters per second, a wind direction of 240° from the north, and a visibility of more than 70 kilometers. R/V *Polar Duke*, however, was located at 64°28' S and 62°15' W, about 50 kilometers southwest of the POLDER scene (centered at 64°22' S and 61°51' W), which may explain the discrepancies in wind speed and direction. The pigment concentration below the aircraft, as estimated from 5 days of measurements (26 to 30 December 1991) during fast grid C (Holm-Hansen and Vernet this issue), is about 7 milligrams per cubic meter value or seven times the value inferred from the POLDER measurements. We note, however, that the R/V *Polar Duke* stations were coarsely spaced and that the 7 milligrams per cubic meter value is subjected to significant uncertainty. Furthermore, the actual optical properties of the phytoplankton in the area of the POLDER measurements may also differ from those used on Morel's (1988) model, as suggested by the chlorophyll-specific diffuse attenuation coefficients reported by Brody et al. (this issue).

The coupled ocean-atmosphere radiative transfer model, which accounts for the essential physics of the problem and yet uses approximate analytical formulas, is adapted to simulate the aircraft POLDER spectral reflectance in areas not influenced by the presence of ice (adjacency effects) and where bottom effects can be neglected. In that case, angular and spectral effects can be described properly, although our verification, based on one POLDER scene, is not conclusive, all the more as the *in situ* and aircraft data were not simultaneous. A dedicated verification study is in order that includes both theoretical and experimental comparisons. Monte Carlo and a successive order of scattering codes (exact codes) are available for theoretical comparisons. On the other hand, *in situ* measurements of bio-optical properties (chlorophyll *a* and phaeopigments, particulate absorption, spectral diffuse attenuation coefficient, beam attenuation coefficient), as well as atmospheric properties (wind speed and direction, aerosol optical thickness) were made aboard R/V *Polar Duke* at the passage of the aircraft. The measurements provide the basis for experimental comparisons.

The model, however, will require modifications. Because the reflectance of ice/snow is high compared to that of water, photons reflected by ice/snow may contribute significantly to the signal measured, especially near the ice. This effect can be taken into account by defining a suitable spatially-averaged reflectance (Tanré et al. 1979). Another modification of importance will be to include the anisotropic effects of the water body reflectance. As Frouin and Hermanto have shown, these effects may not be neglected, especially at high viewing zenith angles and at large scattering angles (reflectance may increase significantly due to the backscattering peak of the phytoplankton phase function). As it stands now, even tnough polarization is not included, our coupled radiative transfer model is sufficiently complete to attempt retrievals of near-surface phytoplankton pigment concentration from the aircraft POLDER data acquired during the 1991-1992 RACER campaign.

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Near-surface phytoplankton pigment concentration in the Gerlache Strait derived from aircraft-polarization-and-directionality-earth-reflectance data (POLDER)

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Several aircraft missions were flown over the Gerlache Strait during the 1991-1992 Research on Antarctic Coastal Ecosystem Rates (RACER) campaign for the purpose of mapping near-surface phytoplankton pigment concentration and primary production, and, hence, to extend spatially the local observations made aboard R/V *Polar Duke*. The aircraft, a Twin Otter operated by the British Antarctic Survey, was equipped with an ocean color imager, the polarization and directionality of the earth reflectance (POLDER) instrument, which measured the specific intensity of sunlight reflected by the atmosphere and ocean in spectral bands centered at 450, 500, 570, 670, and 850 nanometers, as well as the polarization characteristics of the reflected light. Details about the instrument's concept, imaging principle, and characteristics can be found in Frouin et al.

During each mission, the aircraft flew one low-altitude leg at 61 meters with passage over R/V *Polar Duke* and several high-altitude legs at 3,962 meters or 4,572 meters. The objective of flying the high-altitude legs was to map the experimental site. Because the swath at 3,962 meters was 4.9 × 6.5 kilometers and the pixel resolution 17 × 17 meters, it would have required flying six parallel legs to map the Gerlache Strait completely. This was generally not possible, however, because of fuel requirements. The objective of flying the low-altitude leg was to check atmospheric correction schemes and, when passing over the ship, to compare the aircraft measurements with *in situ* optical data.

We focus on the low-altitude leg flown across the Gerlache Strait on 29 December 1991, on an exceptionally clear day (no clouds, low aerosol loading at the surface). During the few days preceding and following that date, 25 December through 30 December 1991, R/V *Polar Duke* surveyed the Gerlache Strait (RACER fast grid C), and the data revealed a strong southwest-northeast gradient of surface phytoplankton pigment concentration (Chlorophyll *a* + phaeophytin), with values reaching 17 milligrams per cubic meter in the southwest and as low as 2 milligrams per cubic meter in the northeast (Holm-Hansen and Vernet this issue). These conditions provided the opportunity to check, over algal biomass levels spanning almost an order of magnitude, the ability of the POLDER instrument to remotely sense ocean color accurately and, thus, to provide quantitative estimates of near-surface phytoplankton pigment concentration. First, we describe the POLDER data and detail the procedure to correct the data for atmospheric effects. Then, we present the results, namely POLDER estimates of pigment concentration along the aircraft subtrack, and we compare the estimates with values measured during fast grid C. Finally, we discuss the accuracy of the estimates in terms of potential sources of errors, in particular, the specific optical properties of the phytoplankton in the Gerlache Strait and the anisotropy of the water body reflectance.

Figure 1 shows the aircraft subtrack across the Gerlache Strait on 29 December 1991. The atmospheric conditions were clear sky, with a horizontal visibility better than 70 kilometers at the surface. Sunphotometer measurements made aboard R/V *Polar Duke*, on the other hand, indicated a rather high aerosol-optical thickness (e.g., 0.2 at 450 nanometers), seemingly in contradiction with the high visibility reported by the ship. The high aerosol-optical thickness, however, was explained by the presence of stratospheric aerosols following the eruption on 15 June 1991, of Mount Pinatubo in the Philippines (Frouin, Panouse, and Devaux this issue). The sea was calm south of Brabant Island, but light foam was observed east of 62° 15' W. Small floes were sometimes within the field of view of the POLDER instrument, but they minimally affected the measurements. Because the leg was flown in the middle of the Gerlache Strait, the effect of sunlight reflection by surrounding ice (adjacency effect) was negligible.

At 161 meters, the pixel size at the ground is about 25 centimeters. Owing to the speed of the aircraft (about 120 knots) and the