

INVERSION SCHEMES TO RETRIEVE ATMOSPHERIC AND OCEANIC PARAMETERS FROM SEAWIFS DATA, NAGW-3498: FINAL REPORT

This investigation (PI. R. Frouin, Co-I: P.-Y. Deschamps) was conducted during the period 1/1/93-12/31/96 with financial support from NASA's Ocean Biology Program in the amount of \$330,535. Resources from the University of Lille, namely instrumentation and the services of two engineers, Drs. Jean-Yves Balois and Pierre Lecomte, were utilized for experiments at the Scripps Institution of Oceanography Pier, La Jolla. During part of the grant period, i.e. from September 94 through August 96, the PI was on leave of absence from the Scripps Institution of Oceanography, detached to NASA Headquarters where he managed NASA's Ocean Biology Program and served as Program Scientist for SeaWiFS and MODIS (ocean aspects). The personnel partly supported by the grant included, in addition to the PI and a programmer analyst, Mr. John McPherson, two post-graduate researchers, Drs. Beatrice Berthelot and Eric Pouliquen, and two graduate students, Ms. Myriam Schwindling and Mr. Bertrand Fougne.

1. Results

Though the original objective of the investigation was to develop new inversion schemes to retrieve atmospheric and oceanic parameters from SeaWiFS data, including neural nets, it was realized that the SeaWiFS project would be better served by focusing on two key issues in satellite ocean color remote sensing, namely the presence of whitecaps on the sea surface and the validity of the aerosol models selected for the atmospheric correction of SeaWiFS data. Therefore, experiments were designed and conducted at the Scripps Institution of Oceanography Pier, La Jolla to measure the optical properties of whitecaps and to study the aerosol optical properties in a typical mid-latitude coastal environment. CIMEL Electronique sunphotometers, now integrated in the AERONET network, were also deployed permanently in Bermuda and in Lanai, calibration/validation sites for SeaWiFS and MODIS. Original results were obtained on the spectral reflectance of whitecaps (Frouin et al., 1996) and on the choice of aerosol models for atmospheric correction schemes and the type of measurements that should be made to verify those schemes (Swindling et al., 1994, 1997).

Bio-optical algorithms to remotely sense primary productivity from space were also evaluated (Berthelot and Deschamps, 1994), as well as current algorithms to estimate PAR at the earth's surface (Frouin and Pinker, 1995). The PI chaired the "Atmospheric Correction over the Oceans" session of a NASA-sponsored workshop on "Aerosols and Atmospheric Correction" held on April 15-19, 1996 in Washington, DC, which reviewed the issues/problems that remain to be addressed/solved before the atmospheric correction can be qualified as generally accurate over the range of conditions expected to be encountered over the oceans (Tanré et al., 1997). The major results and conclusions are summarized below.

a. The spectral reflectance of sea foam measured at the Scripps Institution of Oceanography Pier was found to decrease substantially in the visible and near-infrared, contrary to findings of previous studies, theoretical as well as experimental. Values in the visible (0.44 μm) were reduced by typically 40% at 0.85 μm , 50% at 1.02 μm , and 85% at 1.65 μm . The spectral effect was explained by the nature of foam, which is composed of large bubbles of air separated by a thin layer of water (foam *stricto-sensu*) and of bubbles of air injected in the underlayer. The presence of bubbles in the underlayer enhances water absorption and, thus, reduces reflectance in the near-infrared. For ocean color remote sensing, affected by the presence of foam and aerosols, the consequences of neglecting the spectral dependence of foam are dramatic. With only a small amount of foam, in the presence of aerosols or not, and thus irrespective of aerosol type, the errors in the retrieved

water reflectance at 0.44 μm are above 0.01, which does not meet the accuracy goal of 0.001 for biology applications. The measurements also indicated that foam significantly affects the retrieval of aerosol turbidity at 0.85 and 1.02 μm for wind speeds above 10 m/s, but impacts minimally turbidity estimates at 1.65 μm .

b. Sun transmittance and sky radiance were measured spectrally at the Scripps Institution of Oceanography Pier, La Jolla during the winters of 1993 and 1994. Sun transmittance was also measured aboard R/V Wecoma and on Catalina Island during the 1994 CALCOFI winter cruise. The data were analyzed 1) to verify whether the aerosol models selected for satellite ocean color remote sensing are adequate and 2) to identify what type of atmospheric optics measurements should be performed to verify atmospheric correction algorithms for satellite ocean color radiances. Aerosol optical thicknesses at 0.87 μm were generally low in La Jolla, with most values below 0.1 after correction for stratospheric aerosols. Values were lower offshore (R/V Wecoma, Catalina Island), and no systematic correlation was found between aerosol characteristics and meteorological conditions. Sometimes, however, small (resp. high) Angstrom coefficients were associated with onshore airflow from the ocean (resp. offshore airflow from land). At such low optical thicknesses, variability in aerosol scattering properties cannot be determined, and a mean background model, specified regionally under stable stratospheric component, may be sufficient for ocean color remote sensing from space. For optical thicknesses above 0.1, two modes of variability characterized by Angstrom exponents of 1.2 and 0.5 and corresponding to Tropospheric and Maritime models, respectively, were identified in the measurements. The aerosol models selected for ocean color remote sensing allowed one to fit, within measurement inaccuracies, the derived values of Angstrom exponent and "pseudo" phase function (the product of single scattering albedo and phase function), key atmospheric correction parameters. Additional aerosol models bring little more. Importantly, the "pseudo" phase function can be derived from measurements of the Angstrom exponent. Shipborne sunphotometer measurements at the time of satellite overpass appear sufficient to verify the atmospheric correction of satellite ocean color radiances.

c. In-situ bio-optical measurements from several oceanographic campaigns were analyzed to derive a direct relationship between water column primary production, P , ocean color as expressed by the ratio of reflectances R_1 at 0.44 μm and R_2 at 0.55 μm , and PAR. The study was restricted to Case I waters, for which the following algorithm was proposed: $\log(P) = -4.286 - 1.39 \log(R_1/R_2) + 0.621 \log(\text{PAR})$ with P in $\text{gC}/\text{m}^2/\text{day}$ and PAR in $\text{J}/\text{m}^2/\text{day}$. Using this algorithm, the rms. accuracy on P is 0.17 on a logarithmic scale, i.e. a factor of 1.5. The requirements for central wavelength, spectral bandwidth, and radiometric noise level were also investigated for the spectral bands to be used by an ocean color space mission dedicated to estimating global primary production and the associated carbon fluxes. Nearly all the useful information is provided by two spectral bands centered at 0.44 and 0.55 μm , but the P accuracy appears to be weakly sensitive to spectral bandwidth, which may therefore be enlarged by several tens of nanometers. The sensitivity to radiometric noise, on the contrary, is strong, and a noise equivalent reflectance of 0.005 degraded the P accuracy by a factor of 2.

d. Current satellite algorithms to estimate PAR at the earth's surface were reviewed. PAR can be obtained directly from top-of-atmosphere solar radiance, which is used to determine the transmissivity of the atmosphere. Since clouds do not absorb significantly at PAR wavelengths, the radiative transfer modeling is generally simplified compared to that for total insolation. The inaccuracies reported, about 10 and 6% on daily and monthly time scales, respectively, are useful for modeling oceanic and terrestrial primary productivity. The large short-term variability in the ratio of PAR and insolation, essentially due to clouds, is reduced at those time scales, suggesting that reasonably accurate PAR climatologies may be obtained from available insolation climatologies (satellite or other). The proposed algorithms, however, require further validation.

Improvements are also needed in situations of cloud heterogeneity and in the presence of snow or ice at the surface.

e. The remaining issues for satellite ocean color remote sensing include the effects of absorbing aerosols, the impact of aerosol vertical structure, the influence of thin clouds in the sensor's field of view, the effect of stratospheric aerosols, the validity of the aerosol models, the influence of whitecaps on the ocean surface, the sensor sensitivity to polarization, the influence of instrument straylight, the impact of angular distribution of water-leaving and glitter radiances, the separation of case I and case II waters, the effects of sensor calibration errors, and the validation of the retrieved water-leaving radiances. The most critical issues, however, are absorbing aerosols and whitecaps. They can affect large oceanic areas and in their presence current atmospheric correction schemes will not perform adequately. For absorbing aerosols, a promising approach might be to use spectral bands in the ultraviolet (as molecular scattering increases with decreasing wavelength, aerosol absorption also increases). Ultraviolet wavelengths might also improve the atmospheric correction more directly, by constraining the aerosol path radiance extrapolated from red and near-infrared wavelengths. For whitecaps, more in-situ measurements are in order, to determine their optical properties and how these properties depend on environmental factors. Ideally, the effective whitecap reflectance should be determined for each pixel. This might be possible using appropriate spectral bands in the near-infrared.

2. Publications

- Schwindling, M., P.-Y. Deschamps, and R. Frouin, 1994: Ground-based optical measurements for the validation of ocean color from space. *Eos Trans.*, **75**, 194.
- Berthelot, B., and P.-Y. Deschamps, 1994: Evaluation of bio-optical algorithms to remotely sense marine primary production from space. *J. Geophys. Res.*, **99**, 7979-7989.
- Frouin, R., and R. Pinker, 1995: Estimating photosynthetically Active Radiation (PAR) at the Earth's surface from satellite observations. *Rem. Sen. Environ.*, **51**, 98-107.
- Frouin, R., M. Schwindling, and P.-Y. Deschamps, 1996: Spectral reflectance of sea foam in the visible and near-infrared: in-situ measurements and remote sensing implications. *J. Geophys. Res.*, **101**, 14,361-14,371.
- Kaufman, Y. J., D. Tanré, H. R. Gordon, T. Nakajima, J. Lenoble, R. Frouin, H. Grassl, B. M. Herman, M. D. King, and P. Teillet, 1997: Passive remote sensing of tropospheric aerosol and atmospheric correction for the aerosol effect. *J. Geophys. Res.*, **102**, 16,815-16,830.
- Gregg, W. W., W. E. Esaias, G. C. Feldman, R. Frouin, S. B. Hooker, C. R. McClain, and R. H. Woodward, 1997: Coverage opportunities for global ocean color in a multi-mission era. *IEEE Trans. Geoscience and Remote Sensing*, accepted.
- Schwindling, M. P.-Y. Deschamps, and R. Frouin, 1997: Verification of aerosol models for satellite ocean color remote sensing, *J. Geophys. Res.*, submitted.